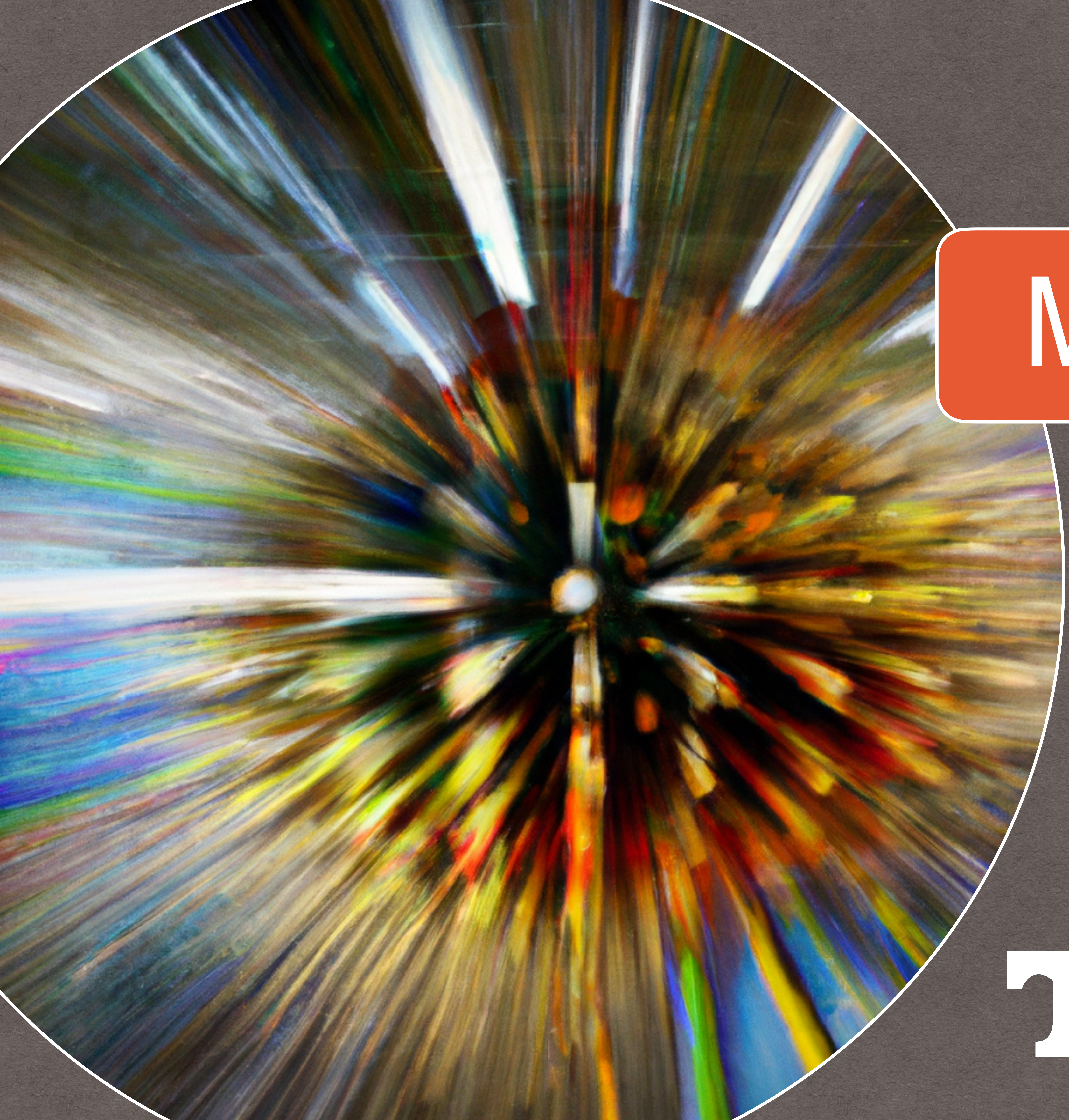


U.S. DEPARTMENT OF ENERGY | Office of Science

MUON COLLIDER

DETECTOR NEEDS FROM FIRST PRINCIPLES

TOVA HOLMES

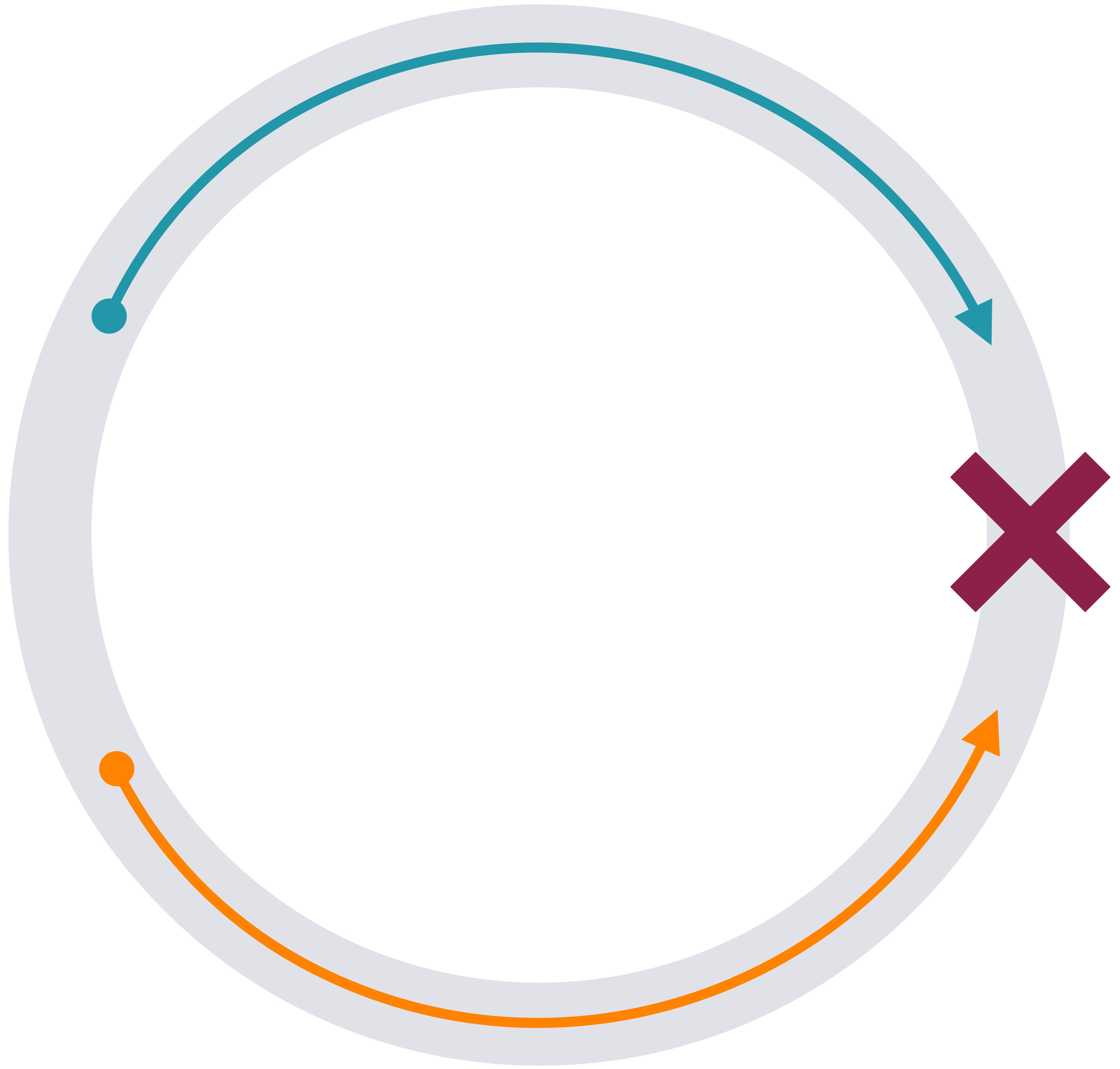
MUON COLLIDER PHYSICS AND DETECTOR WORKSHOP

FERMILAB, DECEMBER 16, 2022

Starting simple

- What's going on inside the collider ring:
  - Circulate two bunches and re-fill when they're depleted
  - time between collisions $t = 33\ \mu s \times \left(\dfrac{L}{10\ \text{km}}\right)$

Large spacing between collisions, ~1000x lower rate than LHC

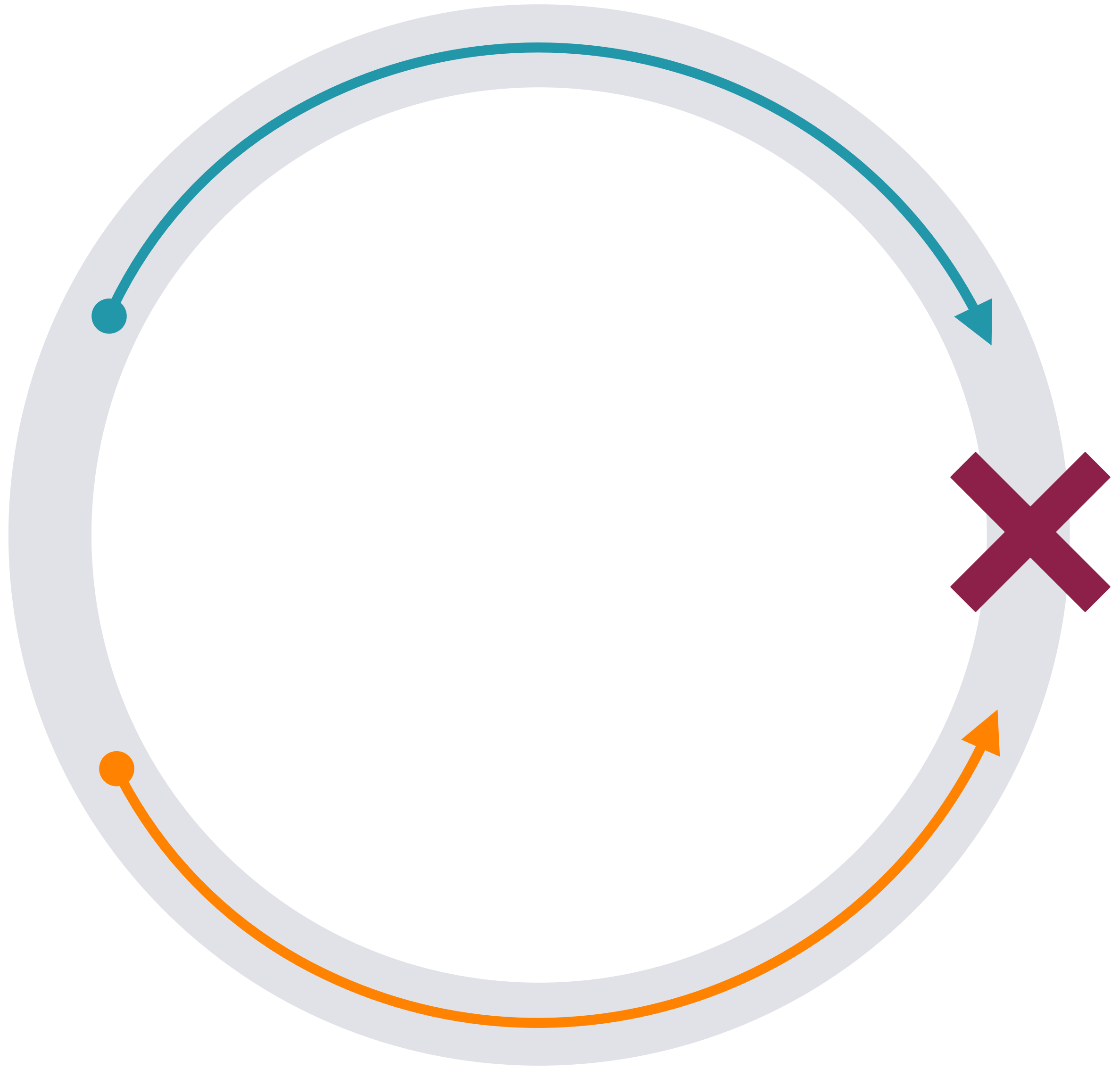


$L = \text{circumference}$

Starting simple

- average decay time in lab frame $\tau'_\mu = 21\ \text{ms} \times \left(\frac{E}{1\ \text{TeV}}\right)$

Need to re-inject at:
~100 Hz for 0.5 TeV beam
~10 Hz for 5 TeV beam



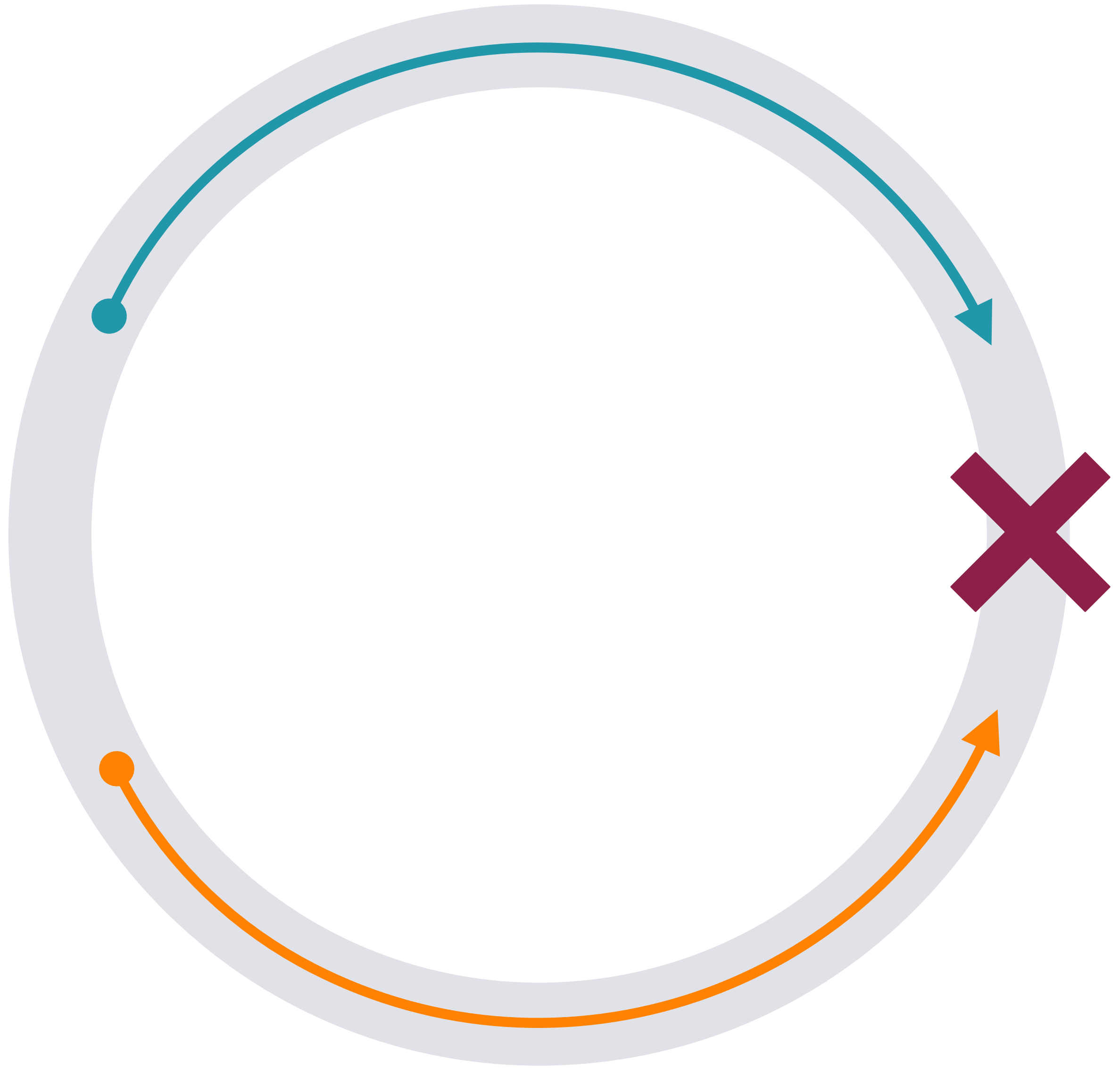
$L = \text{circumference}$
$E = \text{beam energy}$

Starting simple

- average decay time in lab frame $\tau'_\mu = 21 \text{ ms} \times \left(\frac{E}{1 \text{ TeV}}\right)$
- average beam crossings for each injected muon:

$$\langle n_{\text{crossings}} \rangle = 620 \times \left(\frac{E}{1 \text{ TeV}}\right) \times \left(\frac{10 \text{ km}}{L}\right)$$

Luminosity increases proportionally to energy



$L =$ circumference
$E =$ beam energy

Starting simple

For each bunch of 2x10[12], expect around 10[7] decays in this region

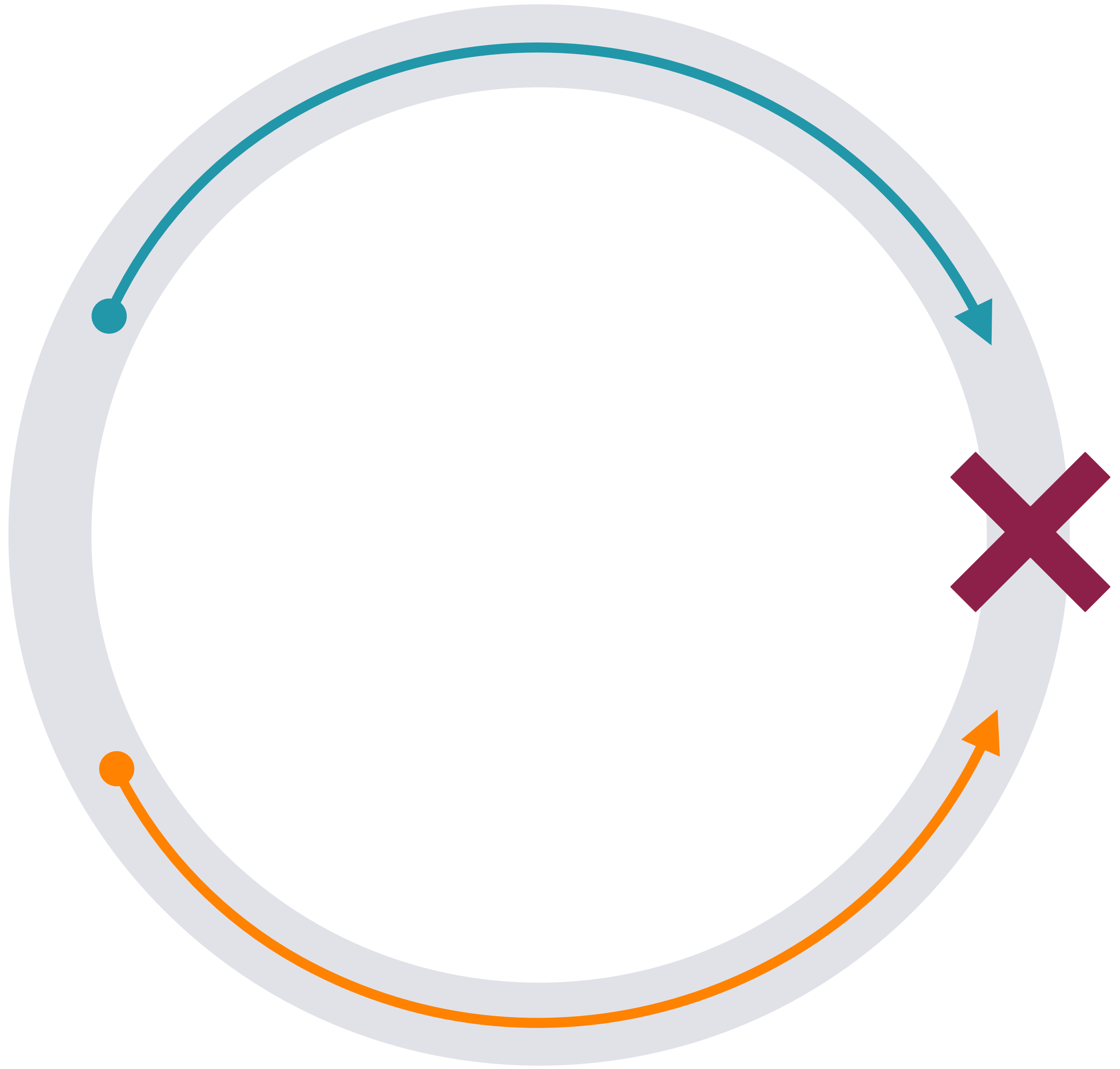
- average decay time in lab frame $\tau'_\mu = 21 \text{ ms} \times \left(\frac{E}{1 \text{ TeV}}\right)$
- average beam crossings for each injected muon:

$$\langle n_{\text{crossings}} \rangle = 620 \times \left(\frac{E}{1 \text{ TeV}}\right) \times \left(\frac{10 \text{ km}}{L}\right)$$

- fraction of muons decaying within 20m of the interaction point:

$$f \approx 6.4 \times 10^{-6} \times \left(\frac{1 \text{ TeV}}{E}\right)$$

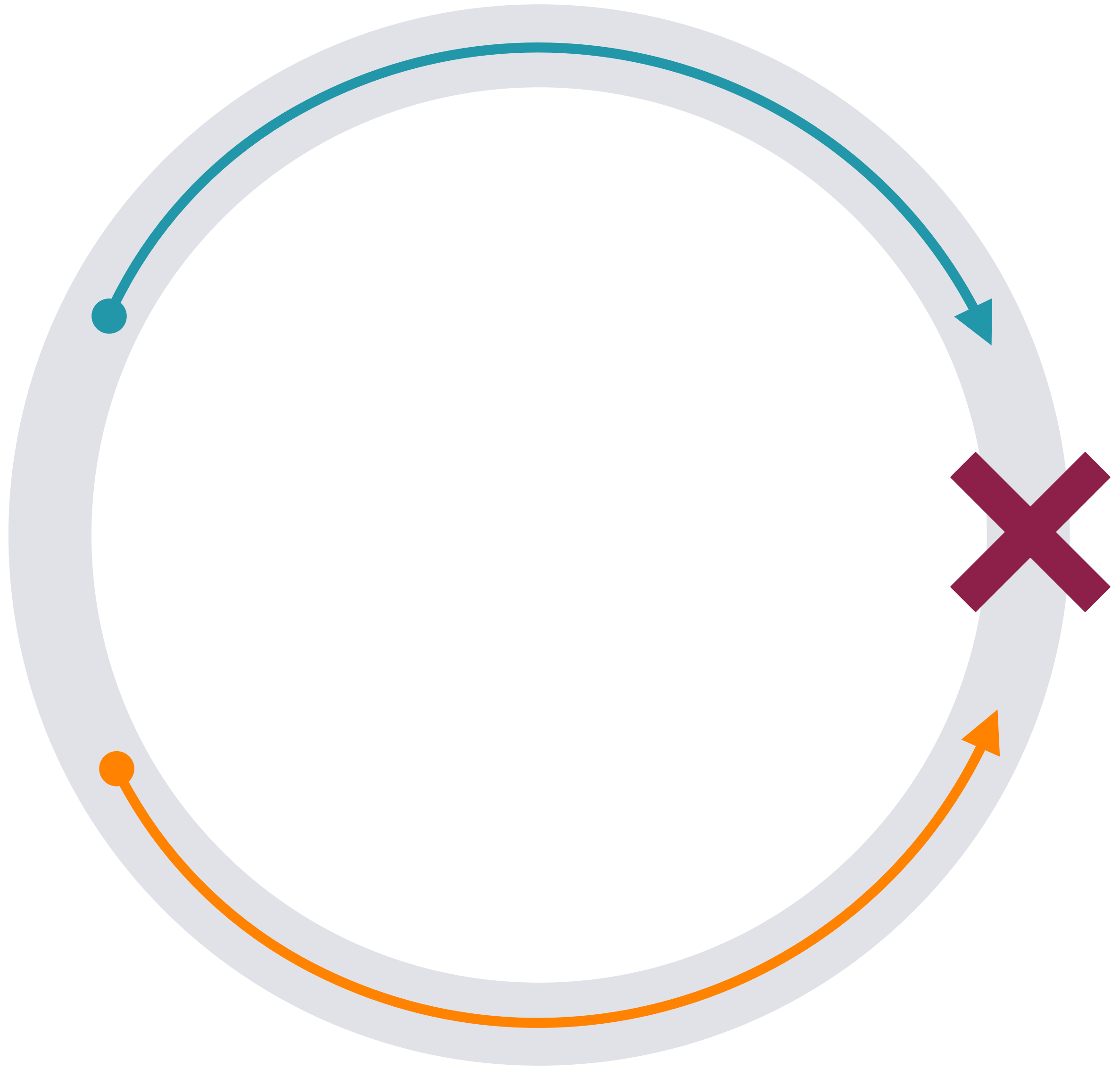
inversely proportional to energy



L = circumference
E = beam energy

Starting simple

- average decay time in lab frame $\tau'_\mu = 21\ \text{ms} \times \left(\frac{E}{1\ \text{TeV}}\right)$
- average beam crossings for each injected muon:
  $$\langle n_{\text{crossings}} \rangle = 620 \times \left(\frac{E}{1\ \text{TeV}}\right) \times \left(\frac{10\ \text{km}}{L}\right)$$
- fraction of muons decaying within 20m of the interaction point:
  $$f \approx 6.4 \times 10^{-6} \times \left(\frac{1\ \text{TeV}}{E}\right)$$
- total energy of decay products within 20m of the interaction point
  $$E_{\text{decay}} = 13\ \text{EeV} \times \left(\frac{n_\mu/\text{bunch}}{2 \times 10^{12}}\right)$$

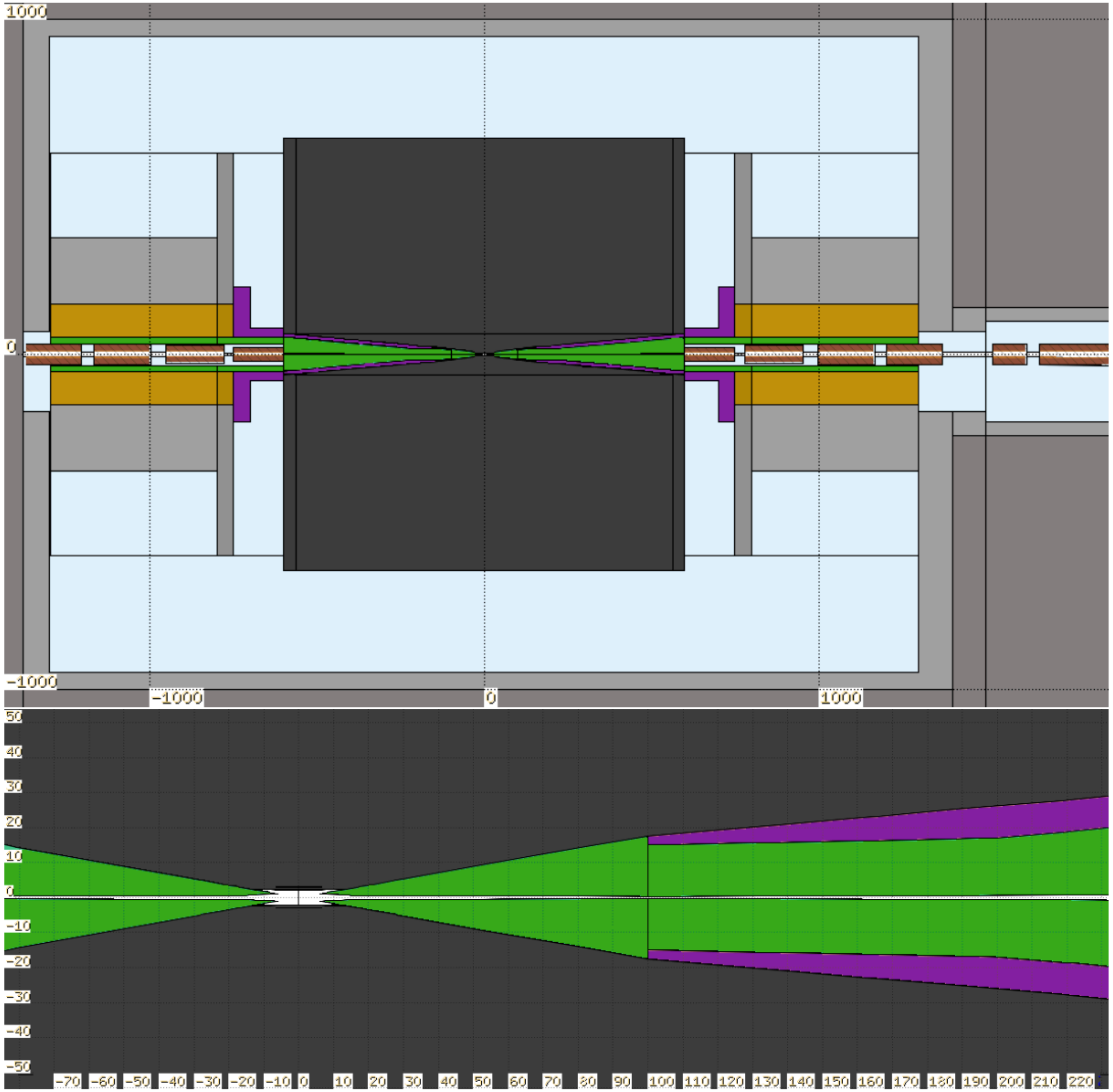


$L = \text{circumference}$
$E = \text{beam energy}$

does not depend on E!

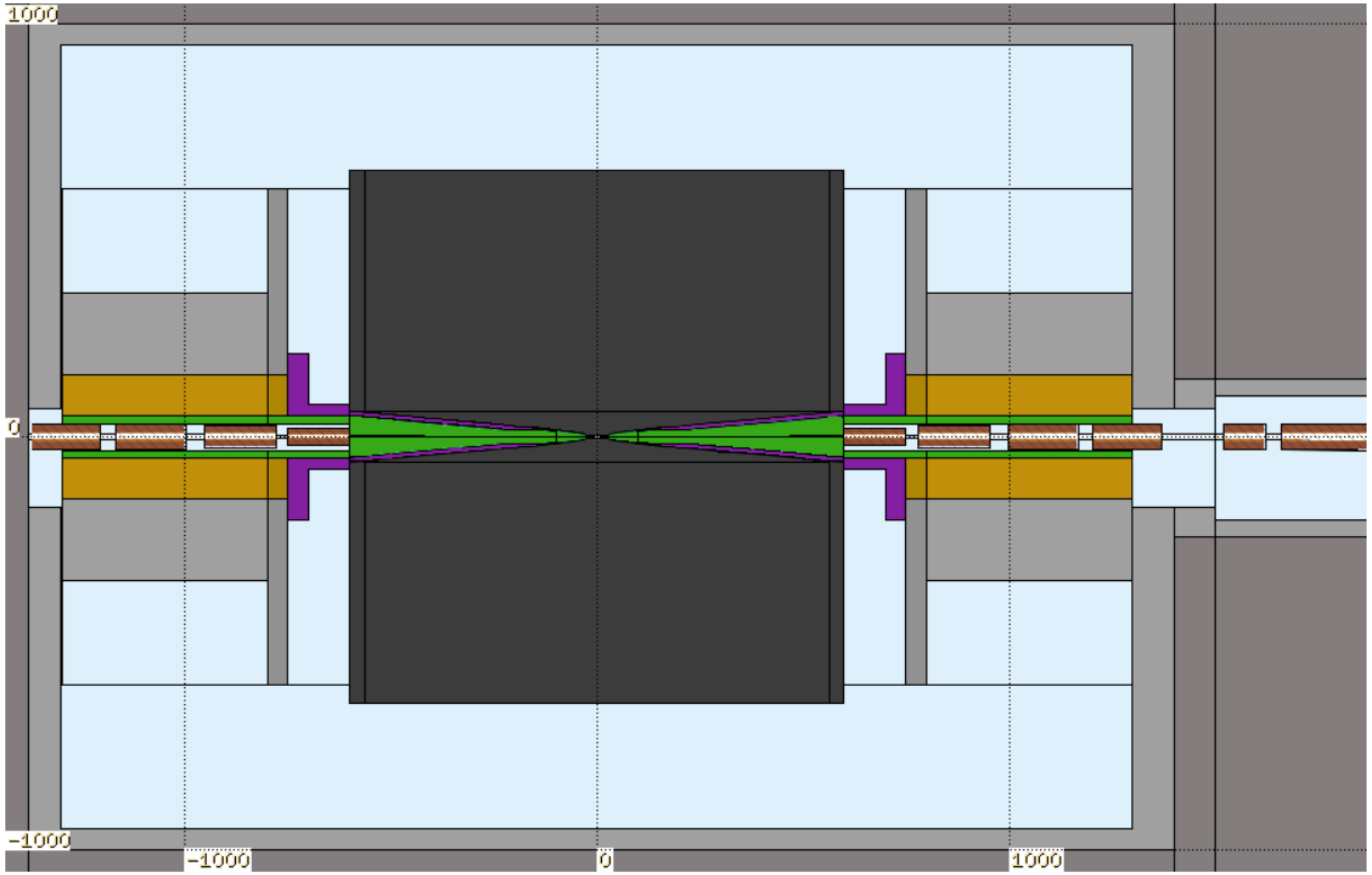
Realistic environment

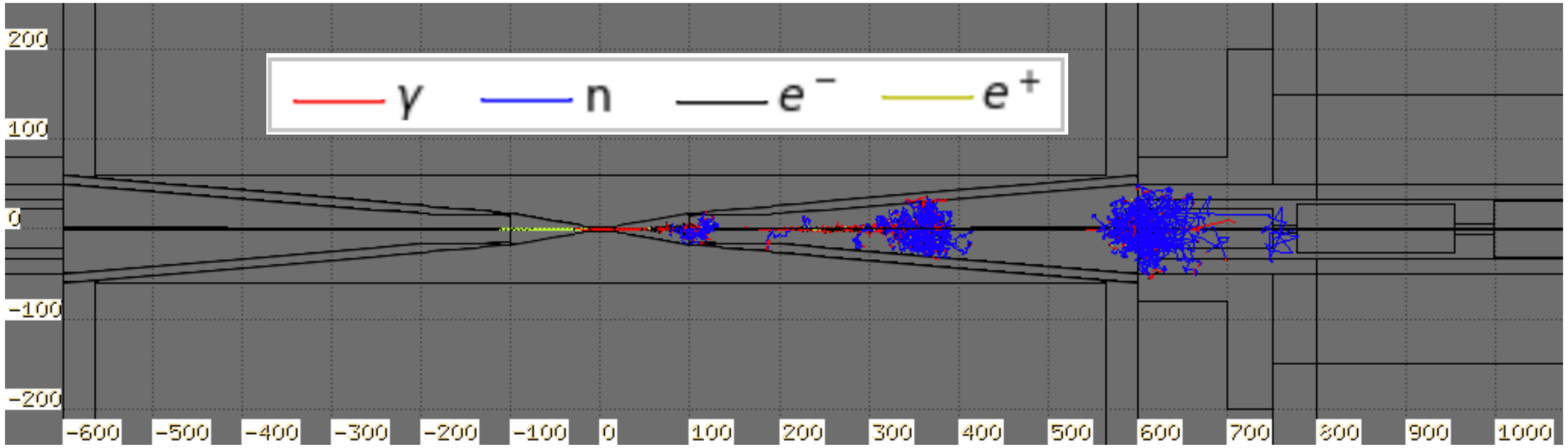
In the detector, flux depends on the interactions of these decay products with the tungsten nozzles



Realistic environment

In the detector, flux depends on the interactions of these decay products with the tungsten nozzles



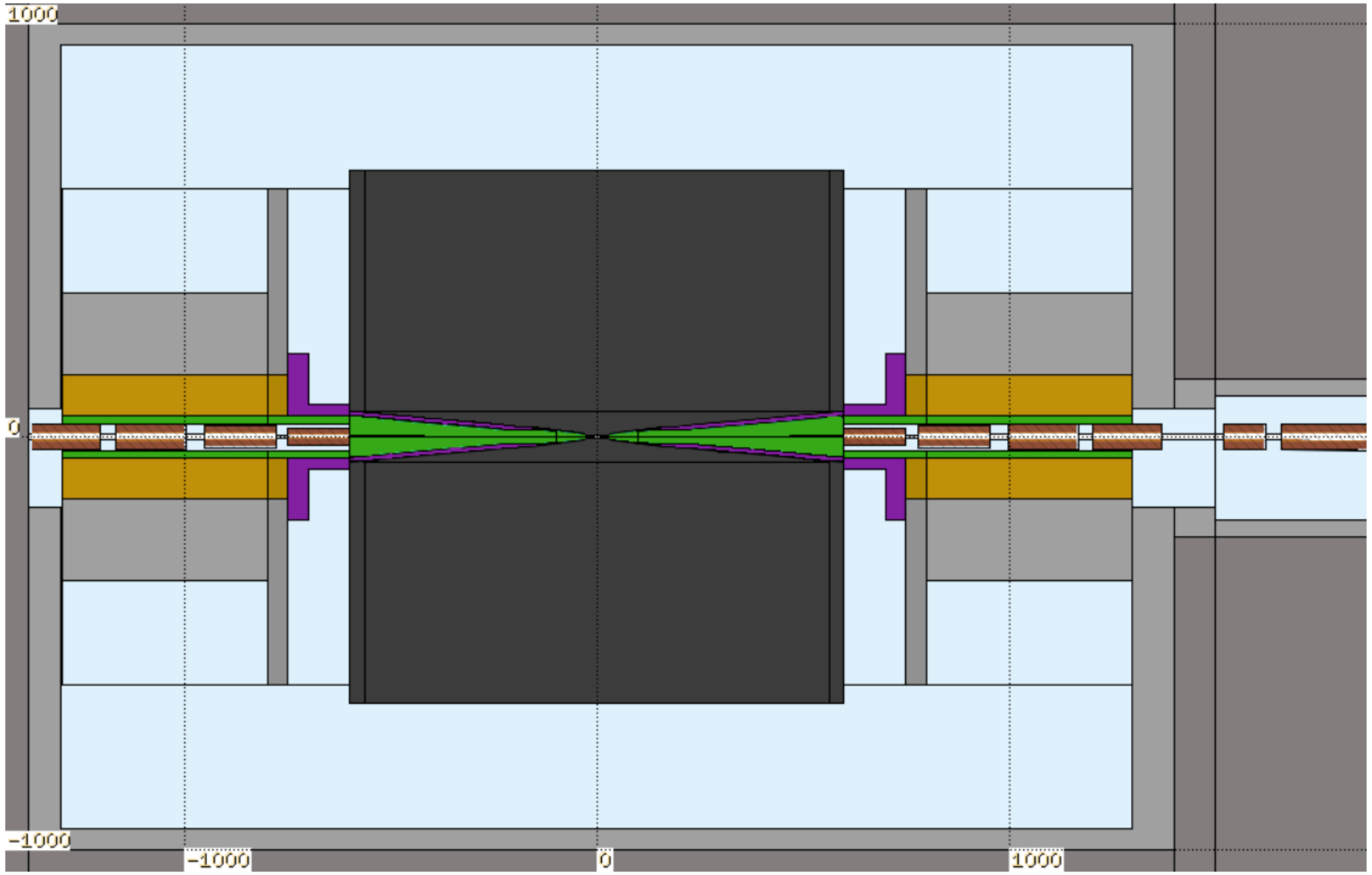


particles resulting from one muon decay

Detector Performance Report

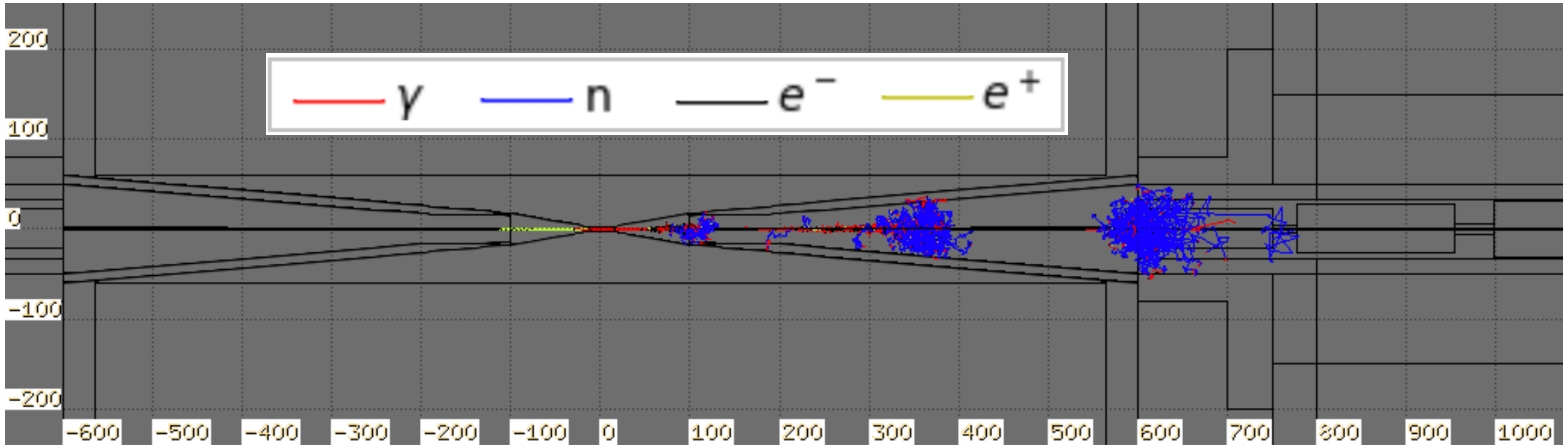
Realistic environment

In the detector, flux depends on the interactions of these decay products with the tungsten nozzles



Exiting particles from one μ- beam, 2x10^{12} muons

Particle (E_{th})	MARS15	FLUKA
Photon (100 keV)	8.6 10^7	5 10^7
Neutron (1 meV)	7.6 10^7	1.1 10^8
Electron/positron (100 keV)	7.5 10^5	8.5 10^5
Ch. Hadron (100 keV)	3.1 10^4	1.7 10^4
Muon (100 keV)	1.5 10^3	1 10^3



F. Collamati et al.

Realistic environment

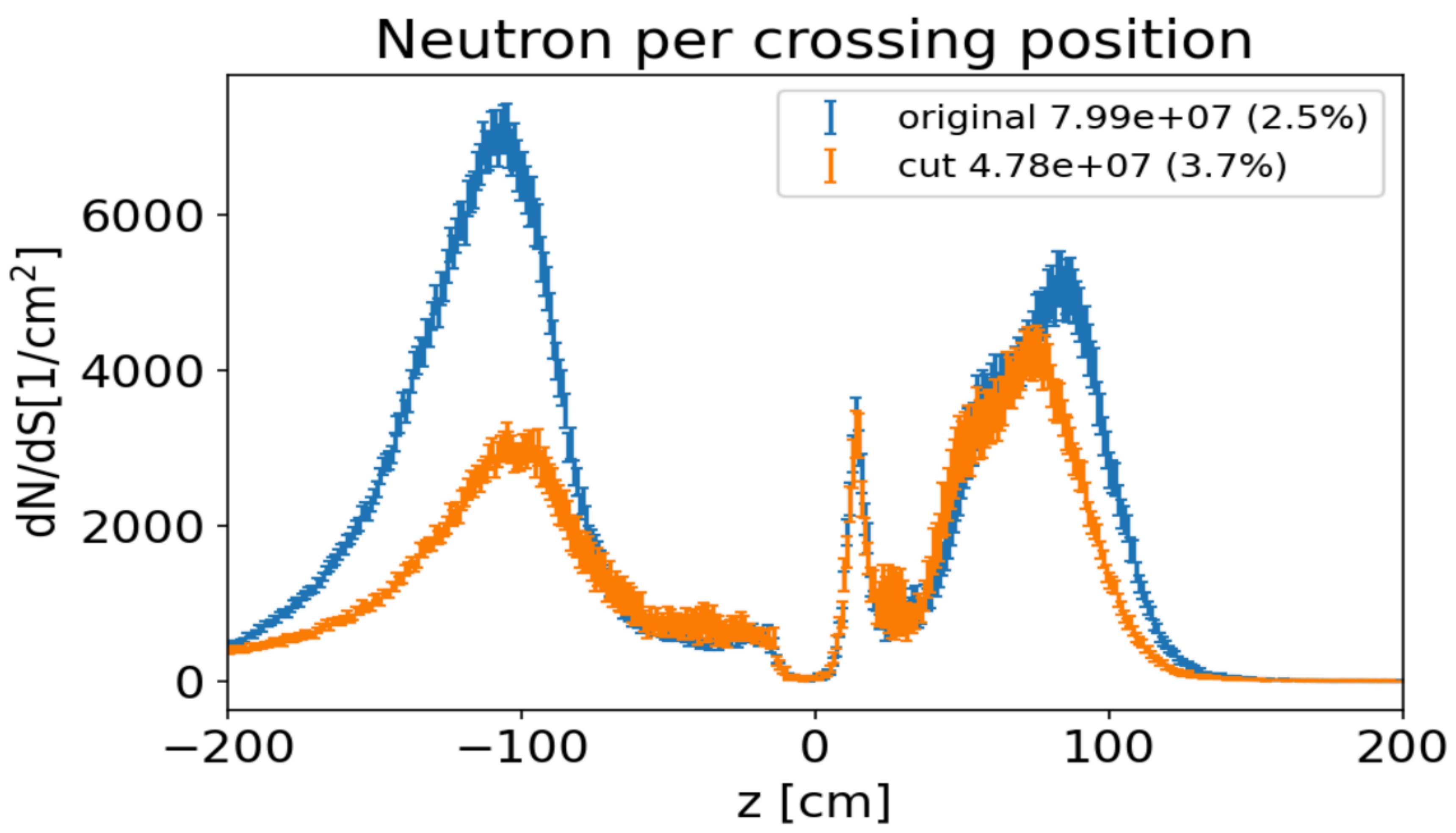
From Donatella's slides…

Monte Carlo simulator	MARS15	MARS15	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	62.5	750	750	1500	5000
μ decay length [m]	$3.9 \cdot 10^5$	$46.7 \cdot 10^5$	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$51.3 \cdot 10^5$	$4.3 \cdot 10^5$	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$170 \cdot 10^6$	$86 \cdot 10^6$	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$65 \cdot 10^6$	$76 \cdot 10^6$	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.3 \cdot 10^6$	$0.75 \cdot 10^6$	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadroms ($E_{h^\pm} > 0.1$ MeV)	$0.011 \cdot 10^6$	$0.032 \cdot 10^6$	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0012 \cdot 10^6$	$0.0015 \cdot 10^6$	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

Same total energy + same nozzle = similar particle flux regardless of beam energy

Exiting particles from one μ- beam, 2x10[12] muons

Particle (E_{th})	MARS15	FLUKA
Photon (100 keV)	$8.6\ 10^7$	$5\ 10^7$
Neutron (1 meV)	$7.6\ 10^7$	$1.1\ 10^8$
Electron/positron (100 keV)	$7.5\ 10^5$	$8.5\ 10^5$
Ch. Hadron (100 keV)	$3.1\ 10^4$	$1.7\ 10^4$
Muon (100 keV)	$1.5\ 10^3$	$1\ 10^3$

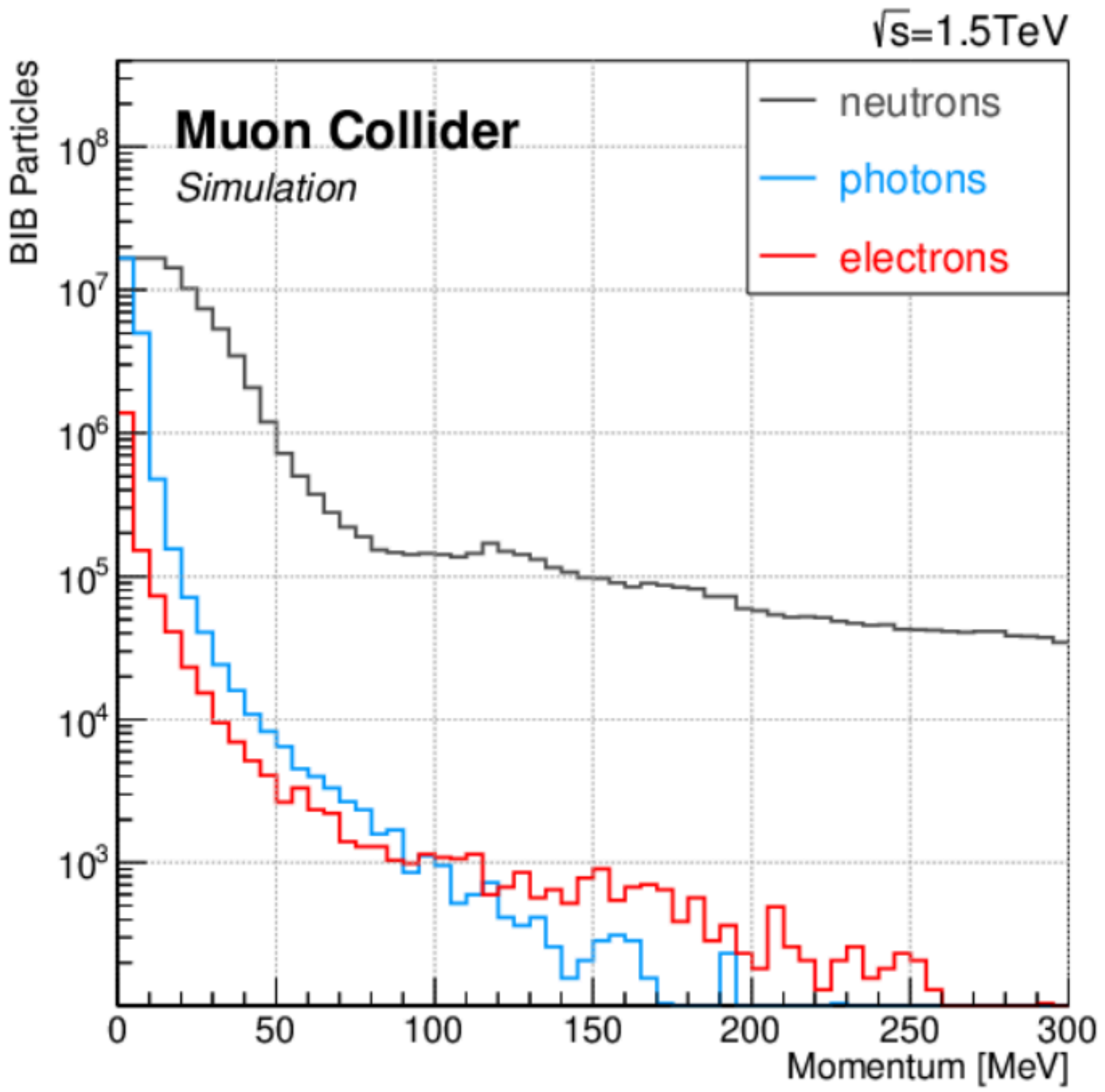


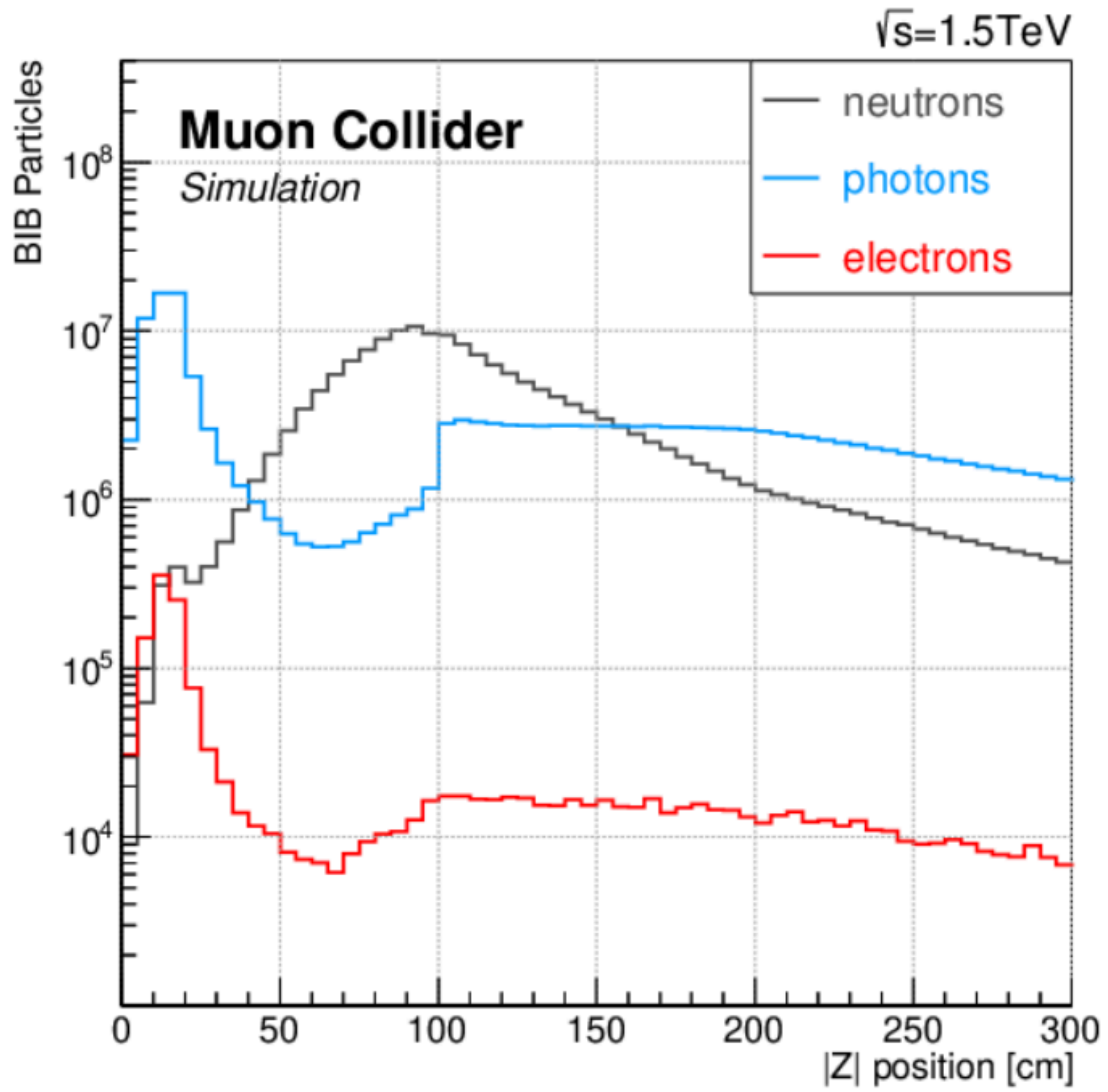
nonetheless, nozzle choices can make big differences!

so now I'm moving away from first principles…

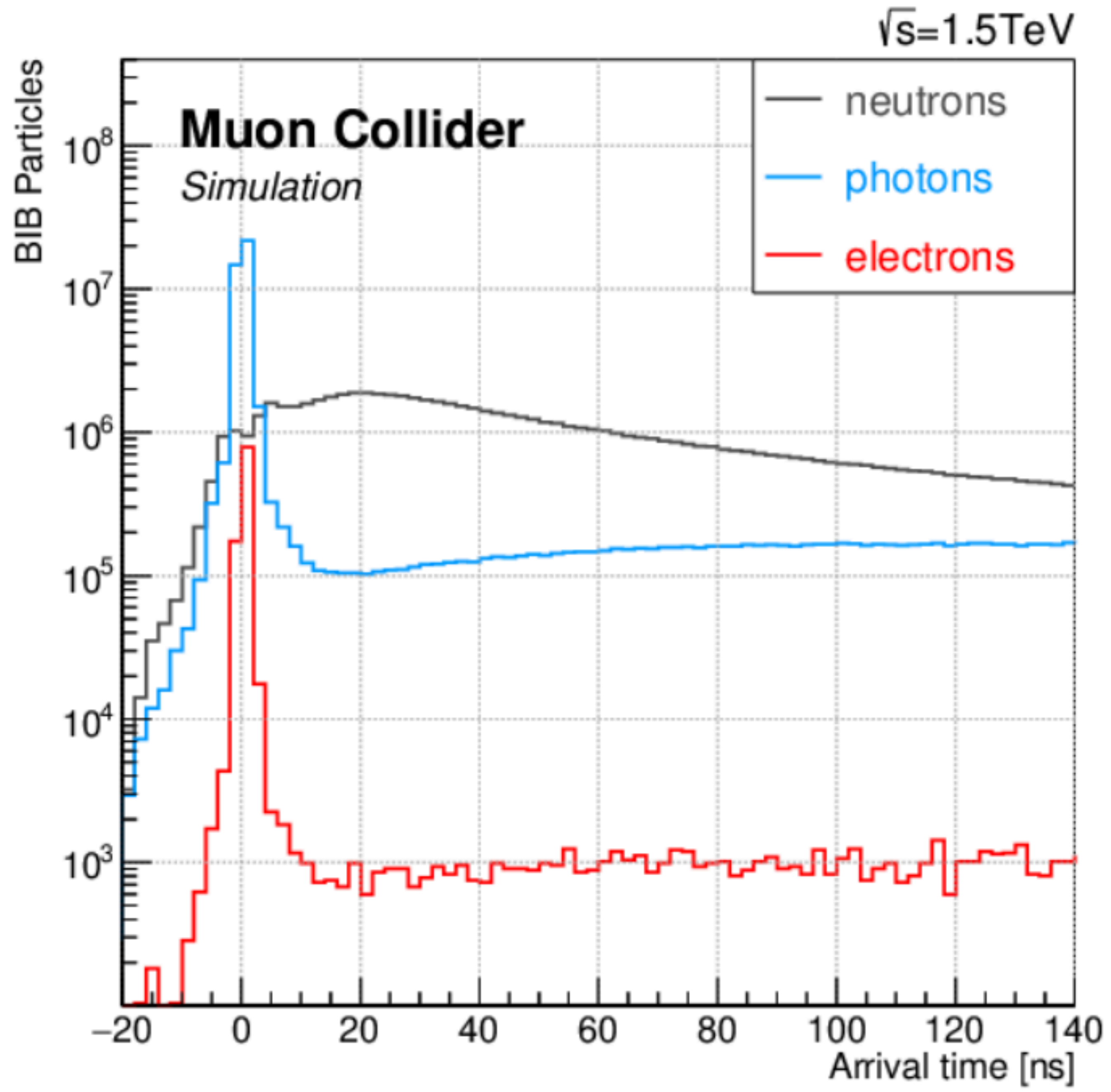
F. Collamati et al.

Realistic environment



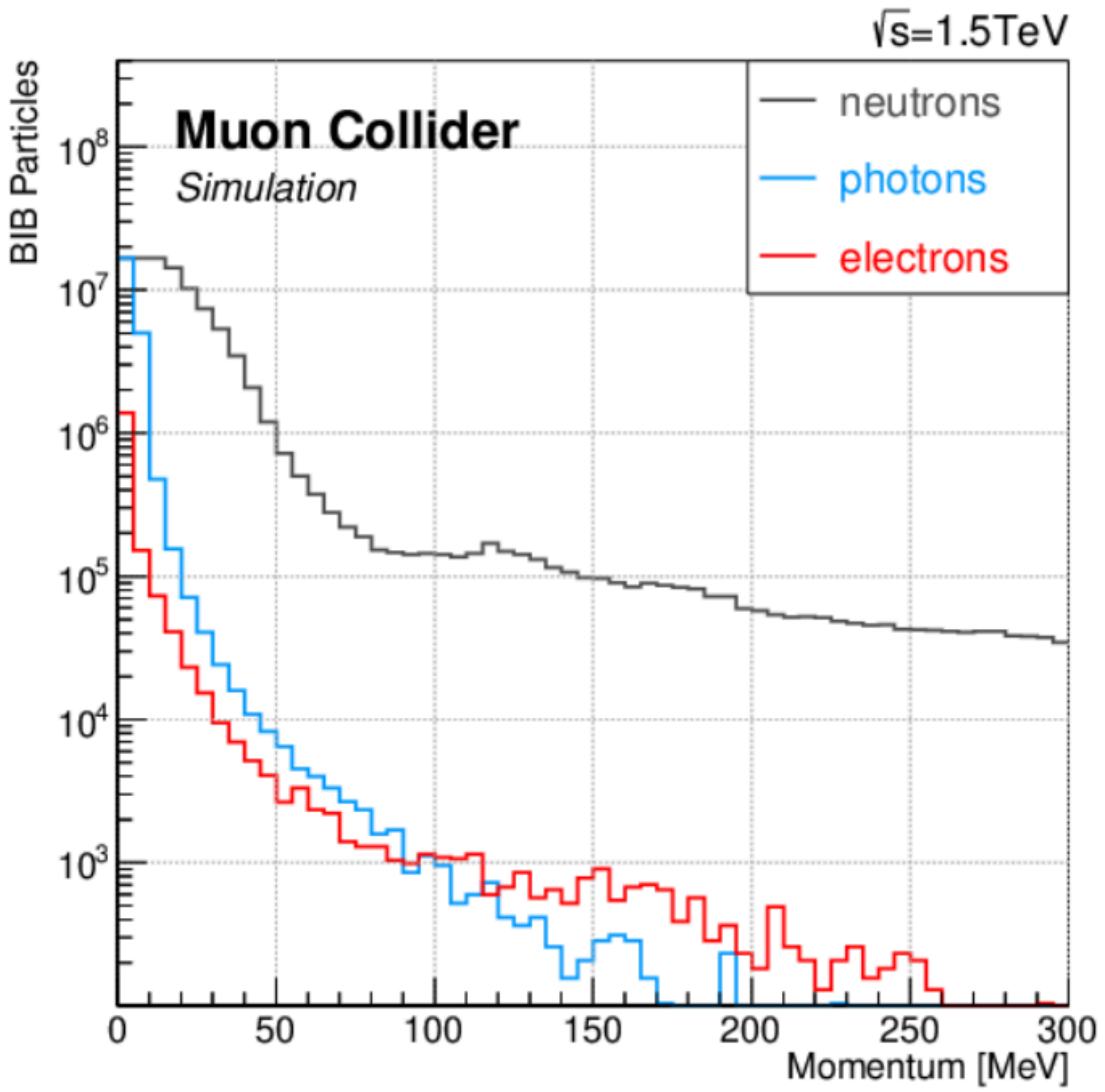


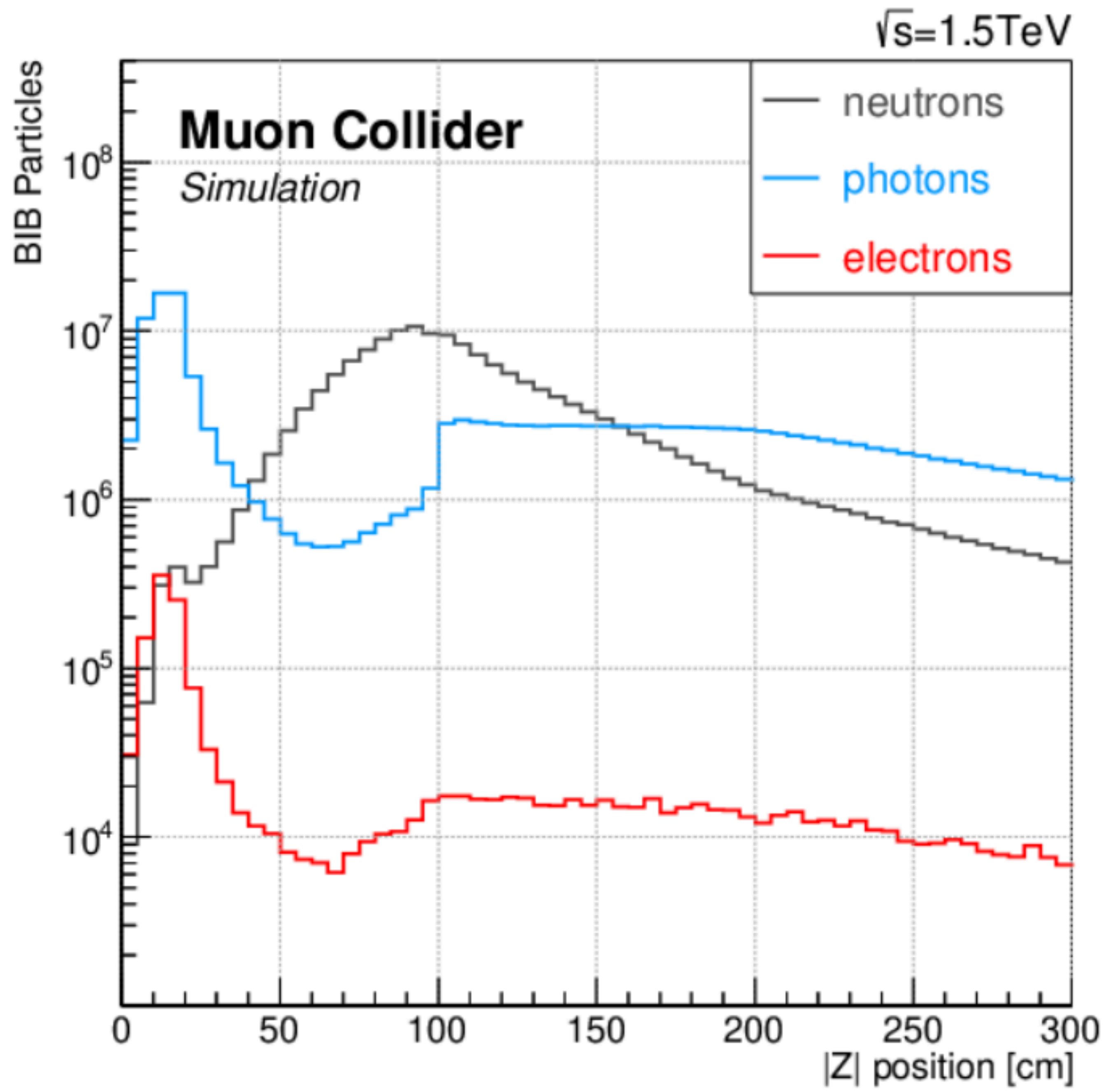
with the "standard" nozzle,
what do our backgrounds look like?



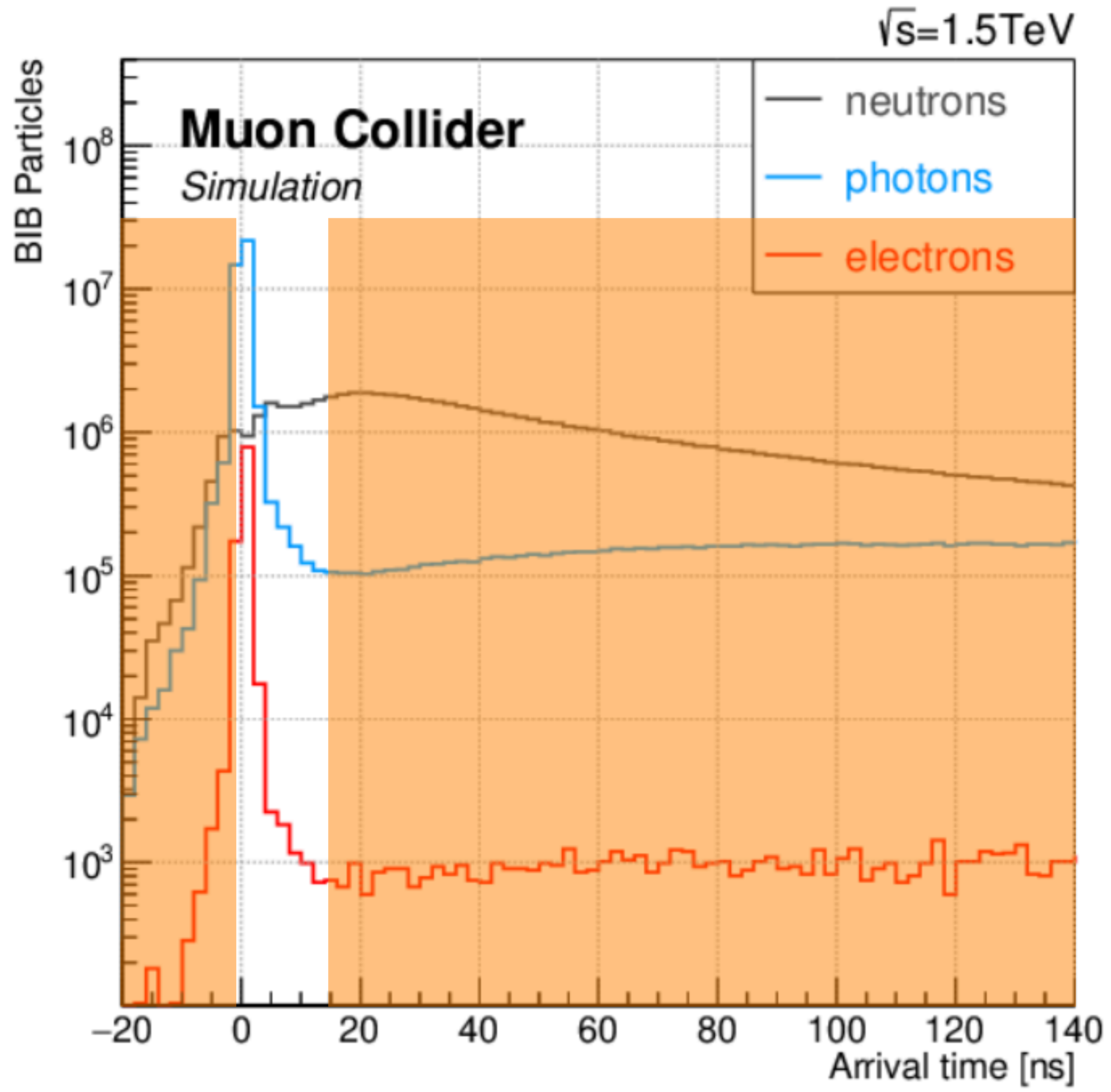
Detector Performance Report

Realistic environment



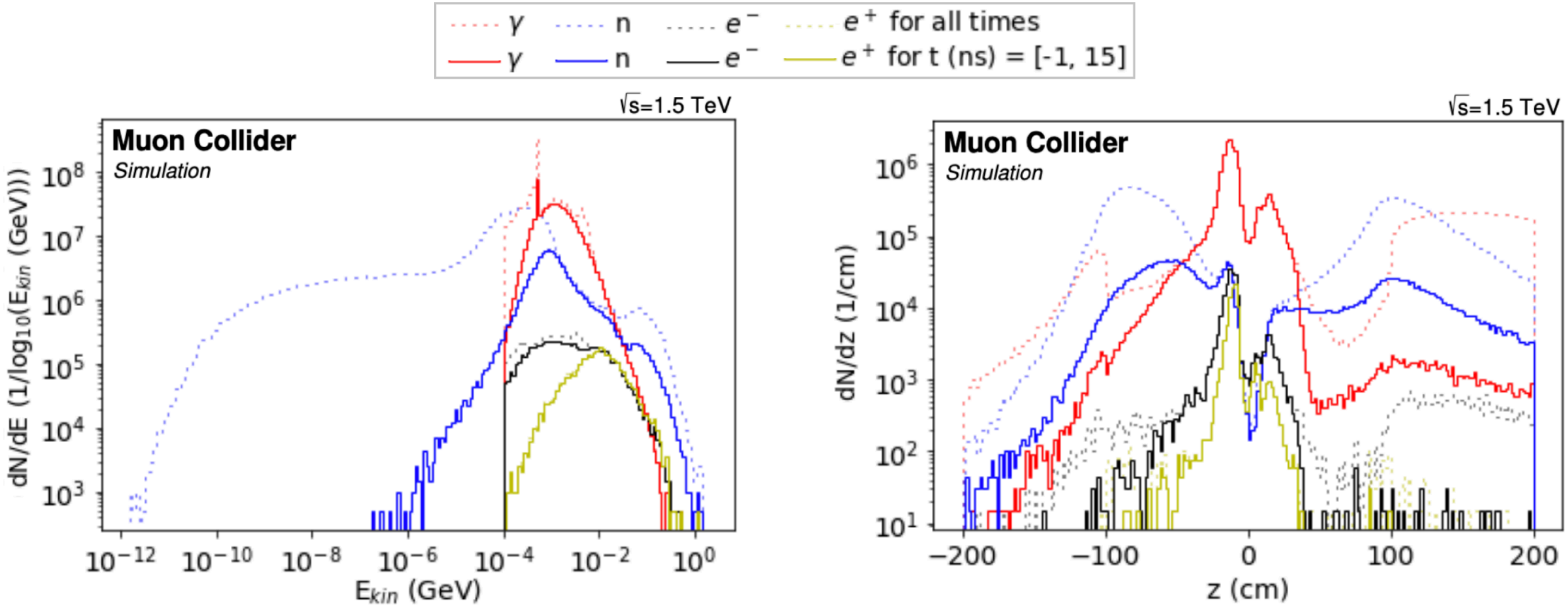


Considering only a small window in time ([-1,15] ns) removes most neutrons, and thus most high energy particles



[Detector Performance Report]

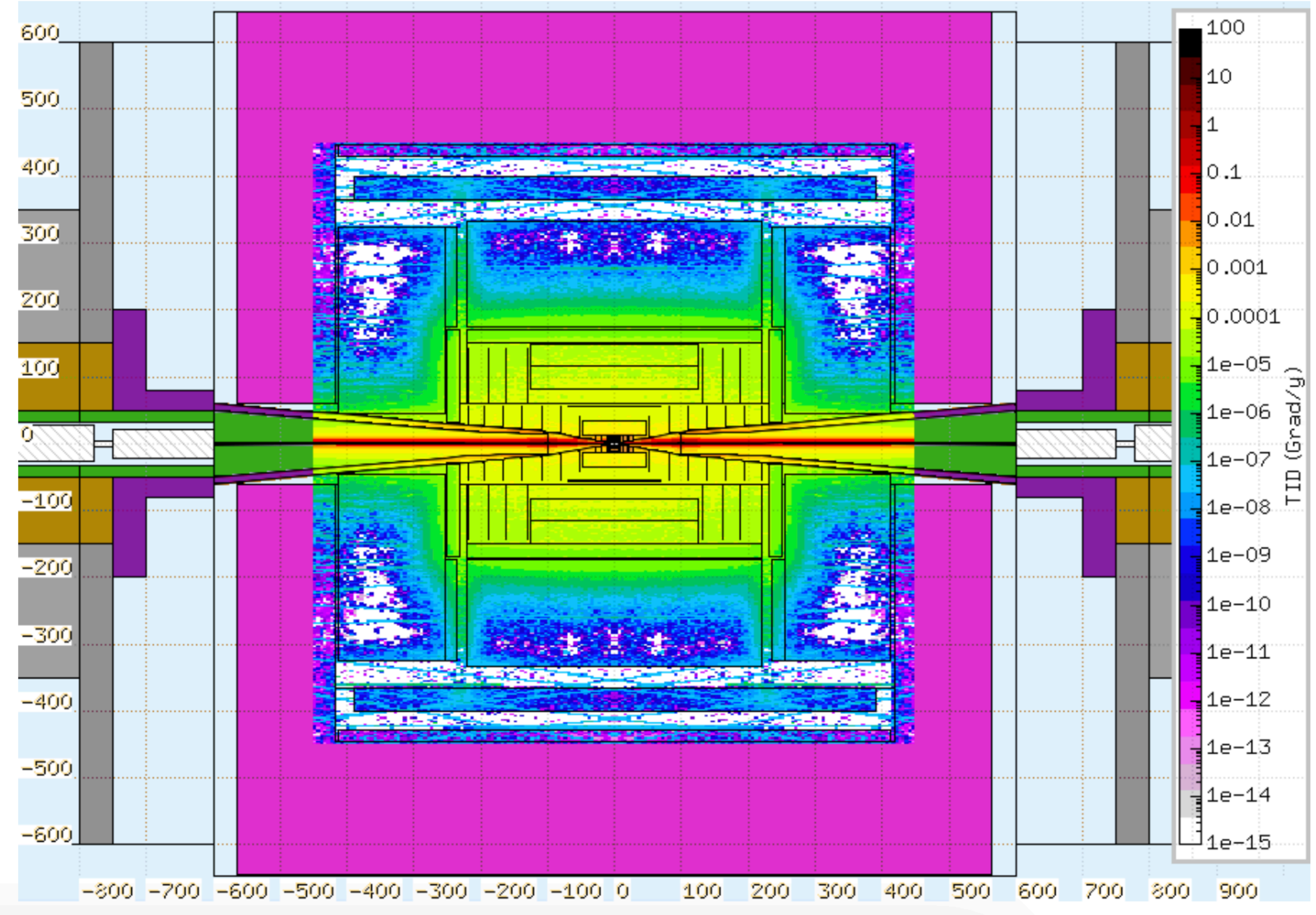
Realistic environment



remaining particles are predominantly low-energy

highest density around ends of nozzles

Realistic environment

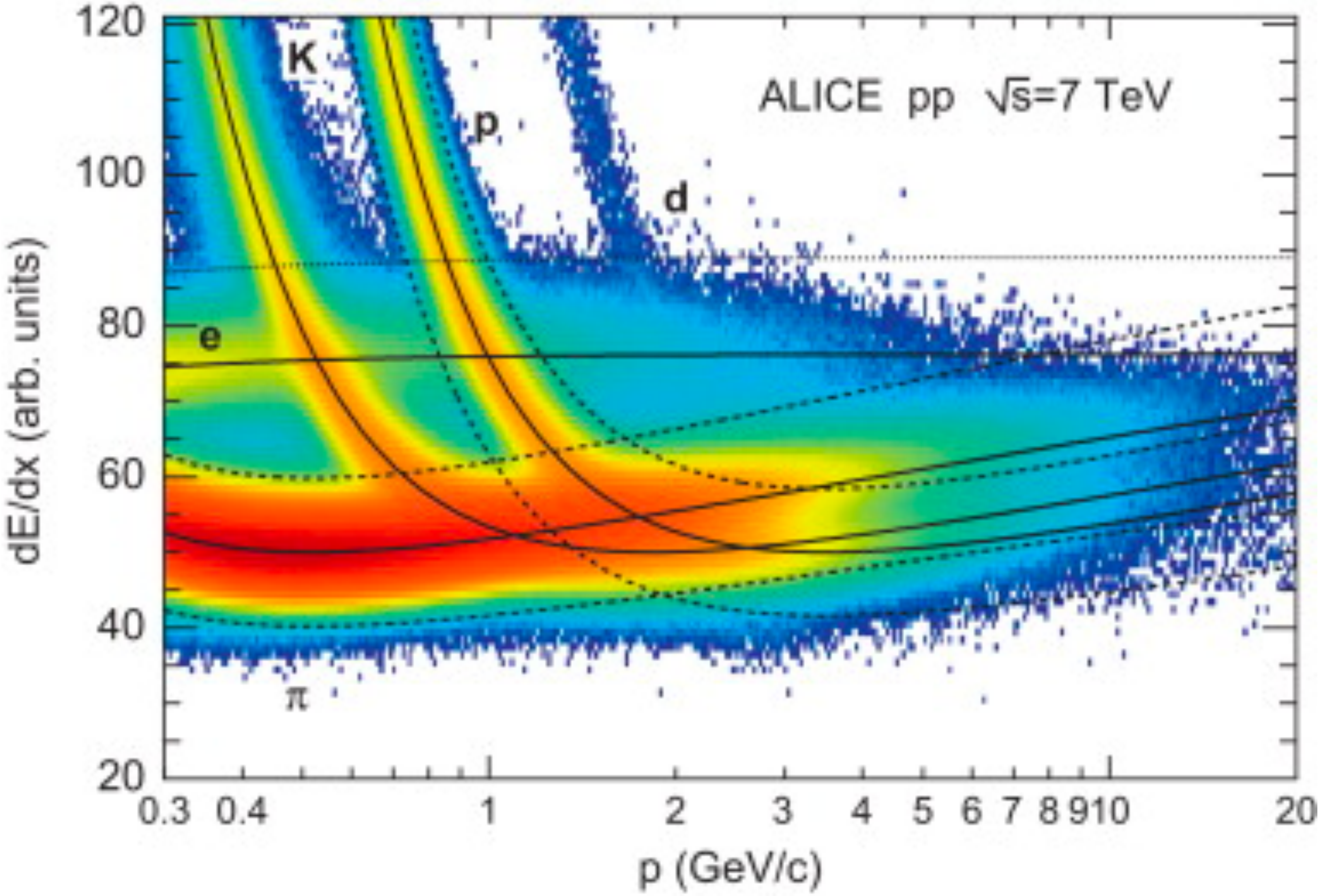


	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

(note: full time range is relevant for radiation damage)

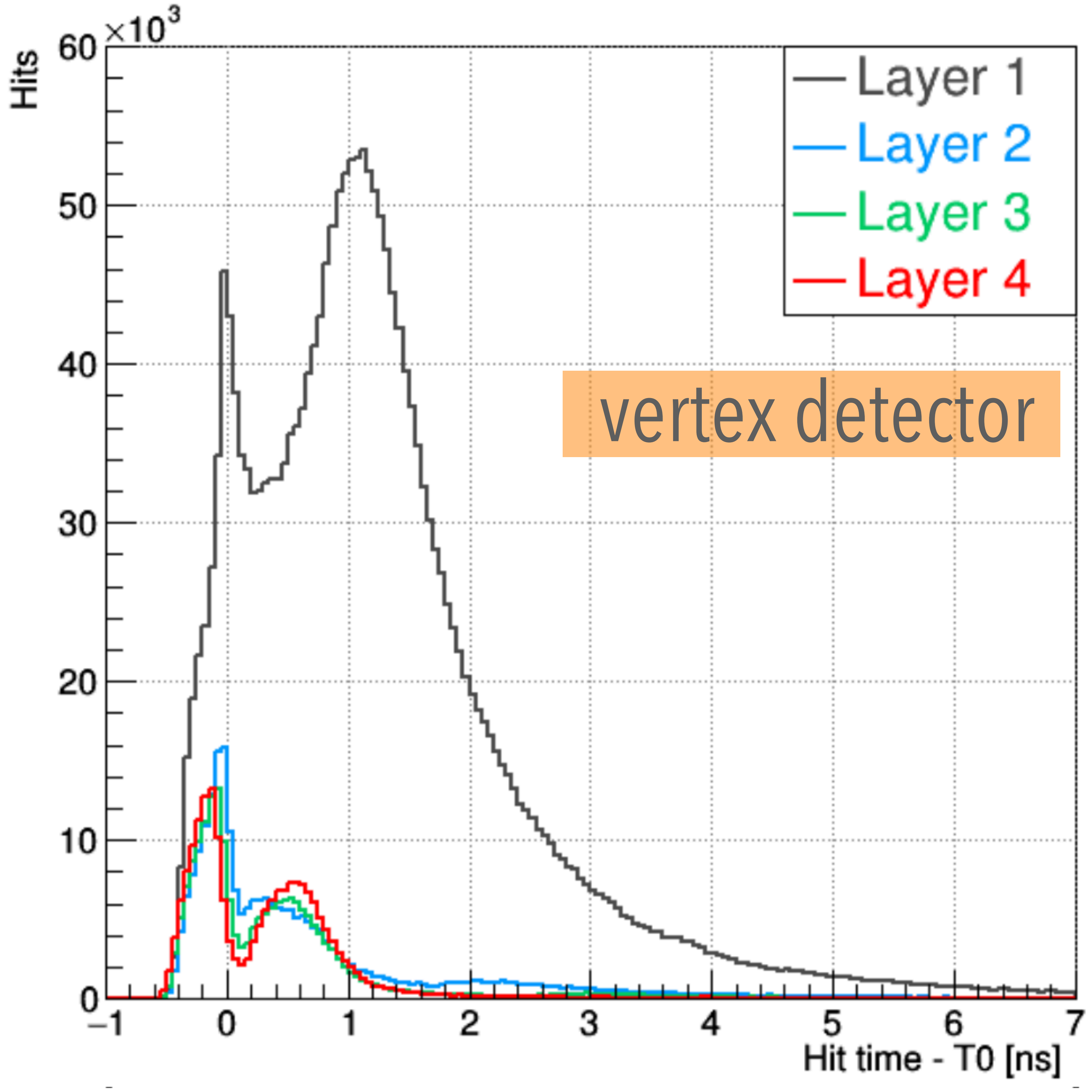
Biggest challenge: tracker

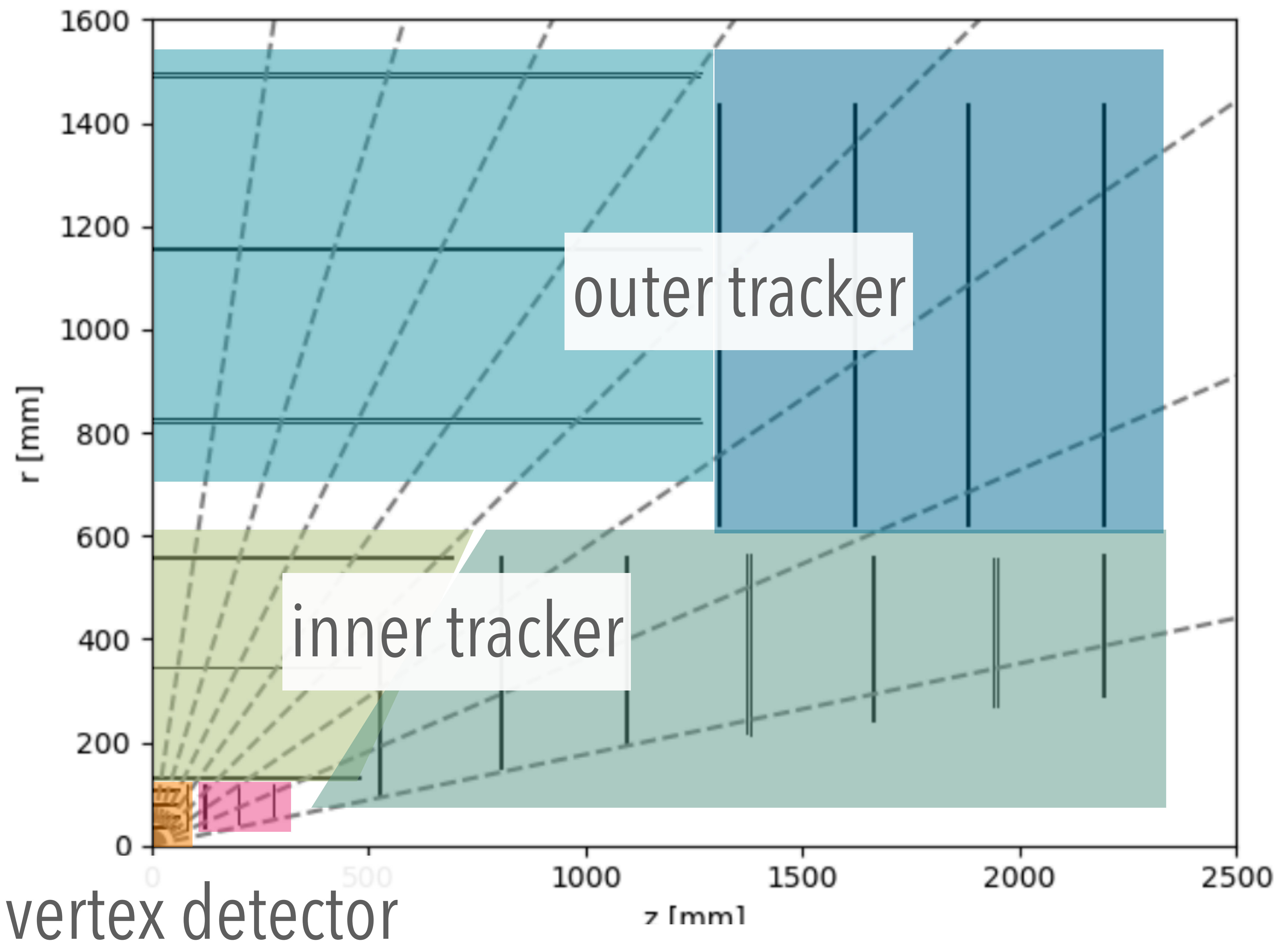
for a tracker: signal size dependent on dE/dx
→ low energy particles create just as much of a signal as high energy particles (if not more)



Biggest challenge: tracker

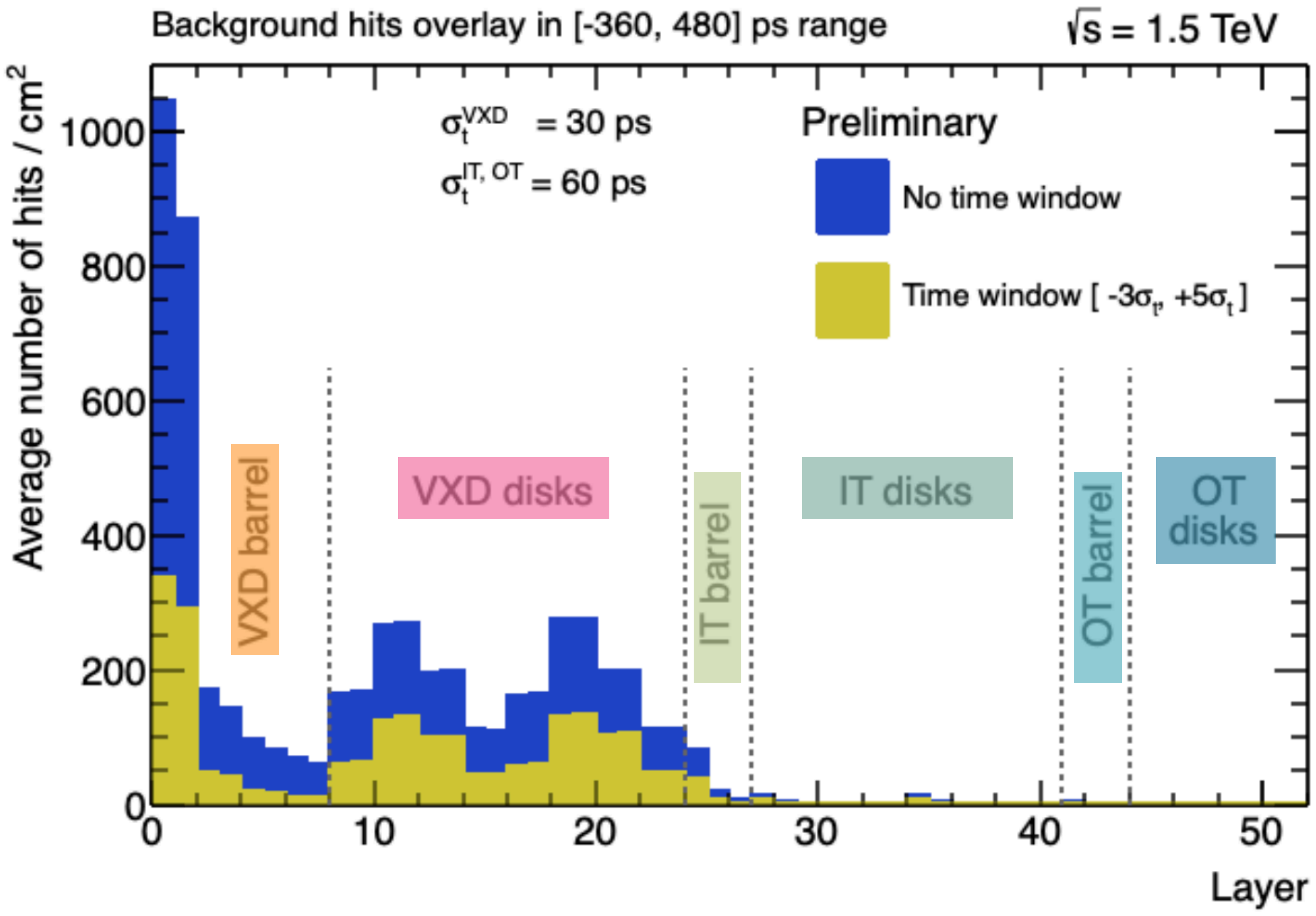
flux in inner layers of the tracker
is extremely high

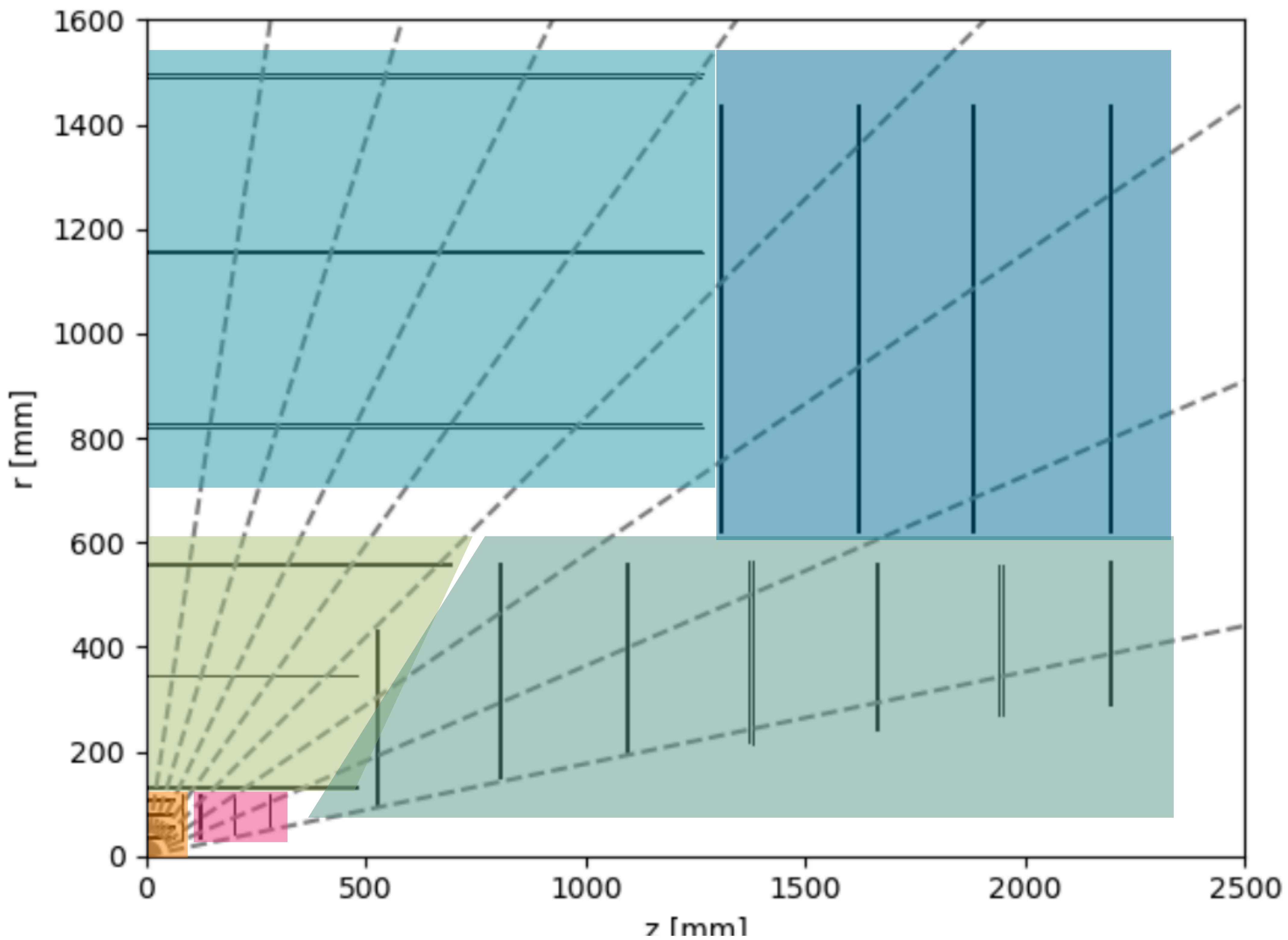




nearly all studies assume tighter timing cuts
are possible: +/- several hundred picoseconds

Biggest challenge: tracker





even with this, still see huge flux in first two layers:

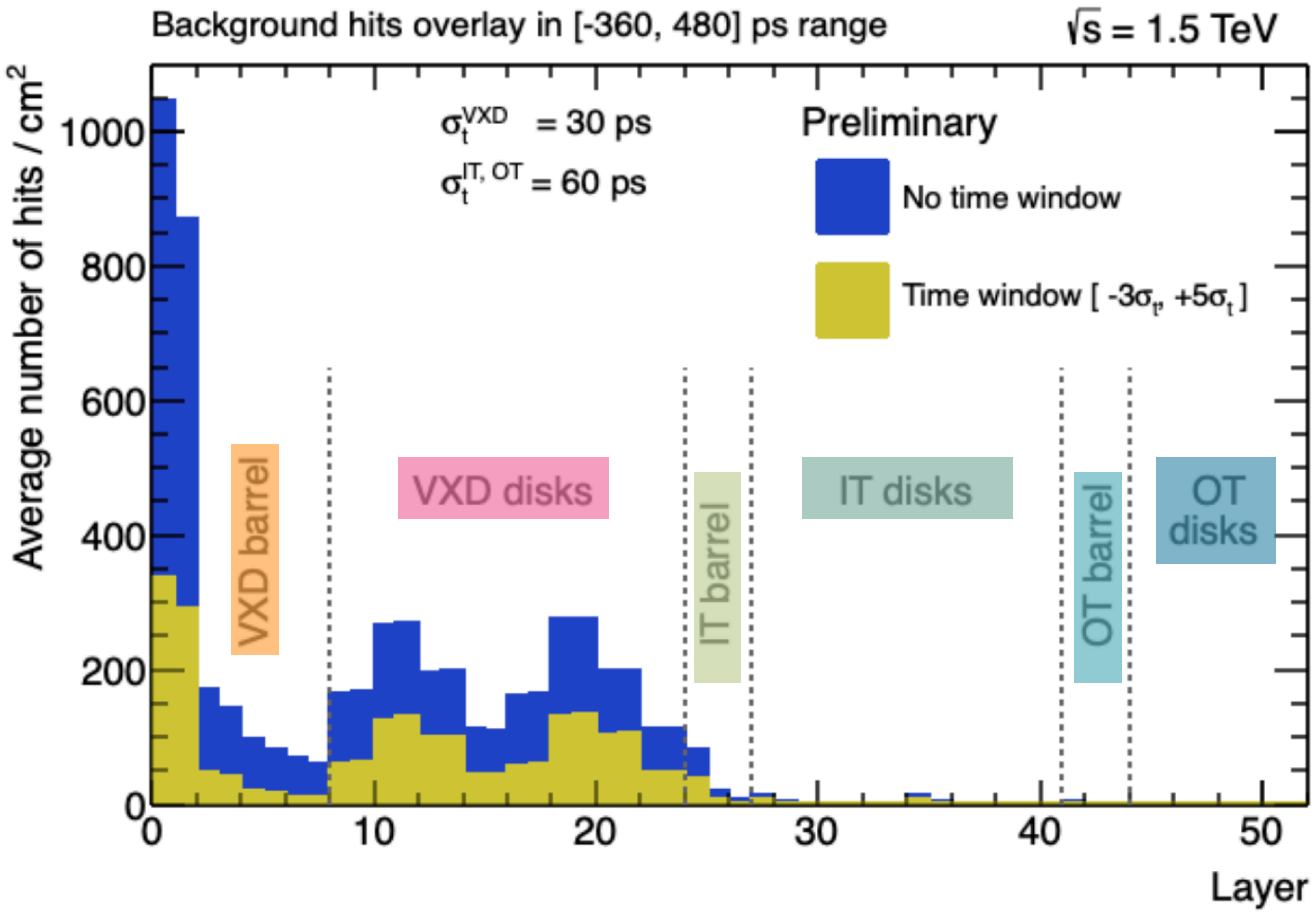
$$l_x \times l_y = \left(\frac{o_{\max}}{n_{\text{hits}}}\right) \text{cm}^2 = 1000\ \mu m^2$$

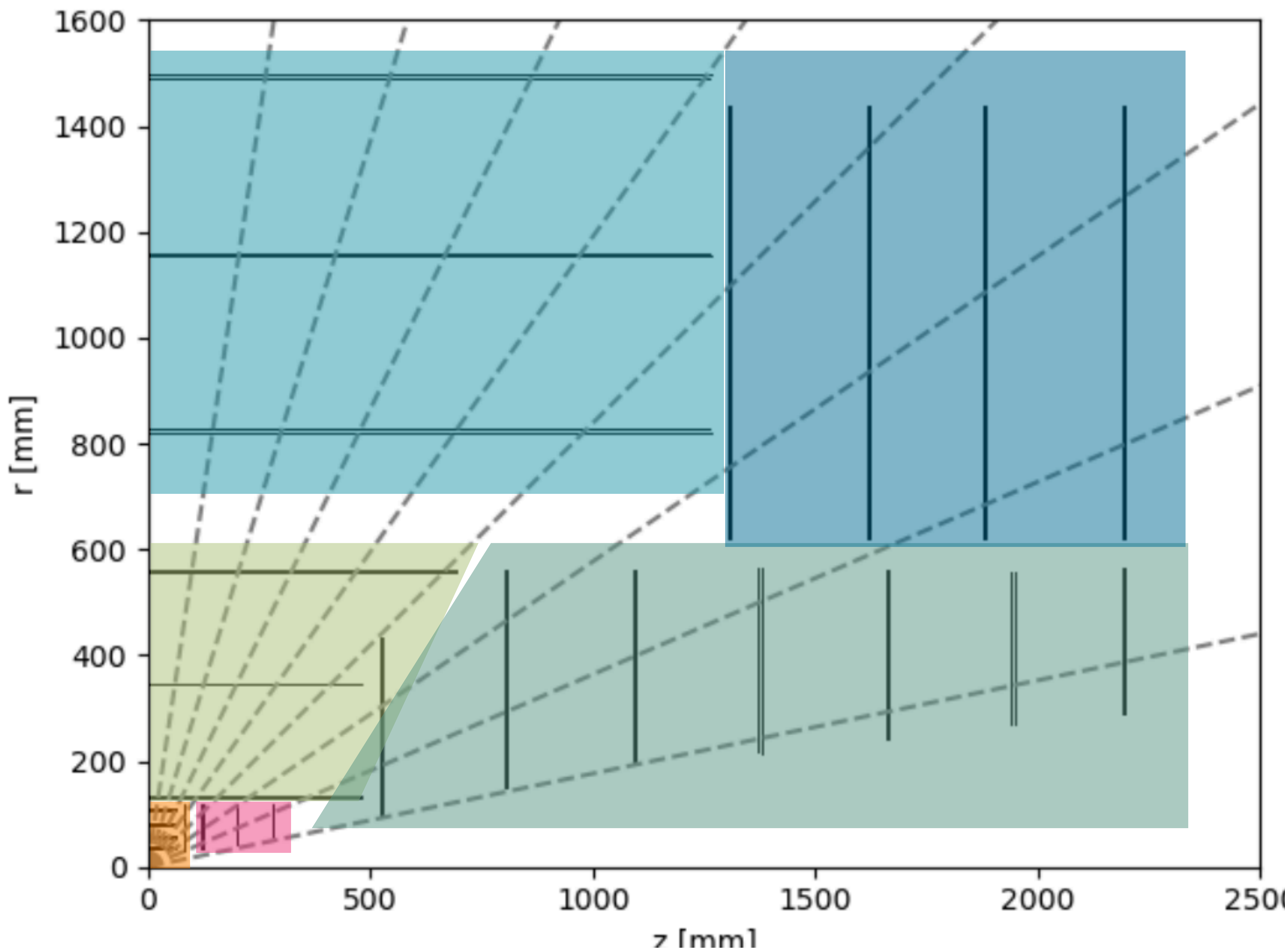
O(1k) hits/cm² →

need O(100k) pixels/cm² for 1% occupancy (30 μm pitch)

Detector Performance Report

Biggest challenge: tracker





even with this, still see huge flux in first two layers:

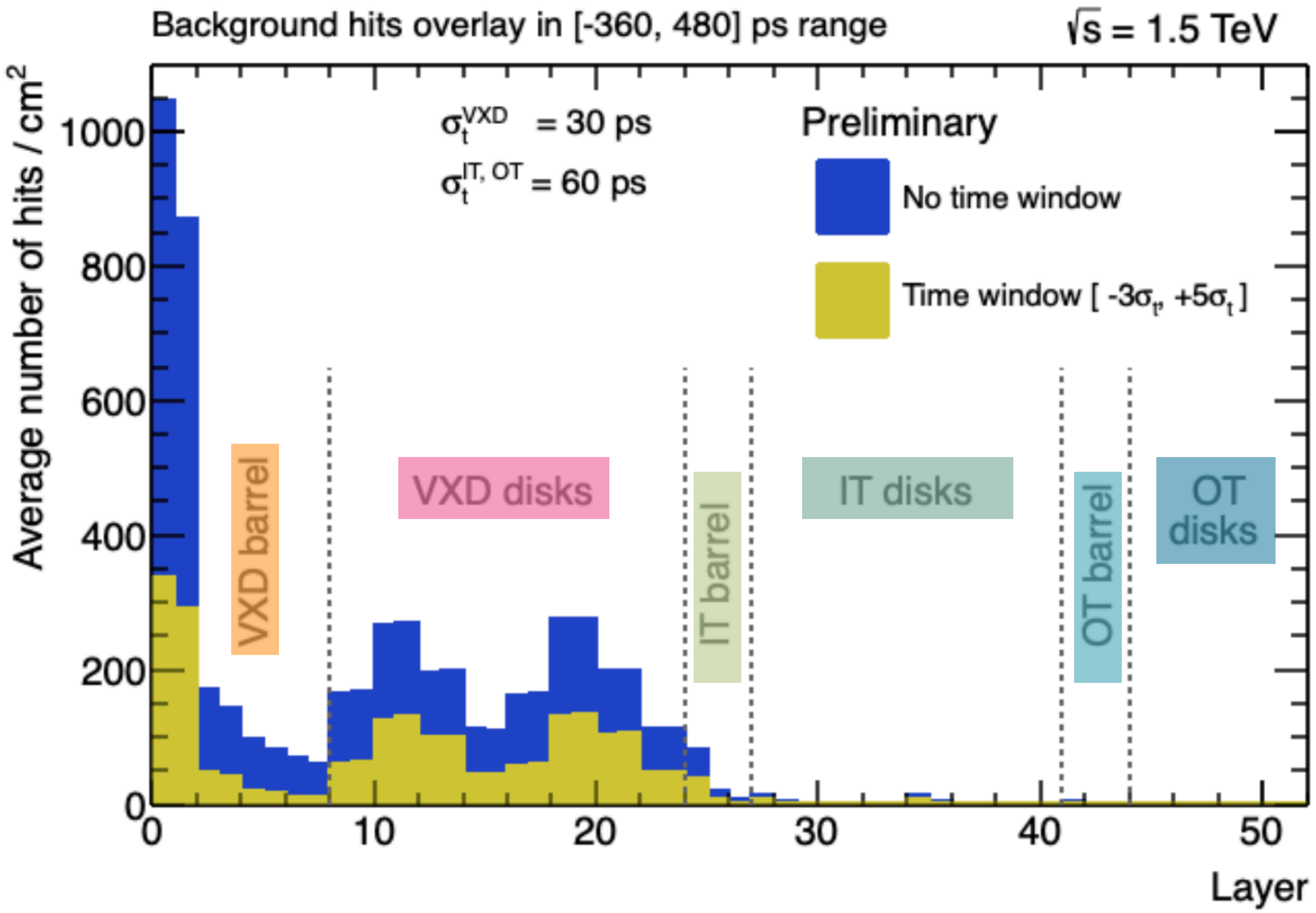
$$l_x \times l_y = \left(\frac{o_{\max}}{n_{\text{hits}}}\right) \text{cm}^2 = 10{,}000\ \mu m^2$$

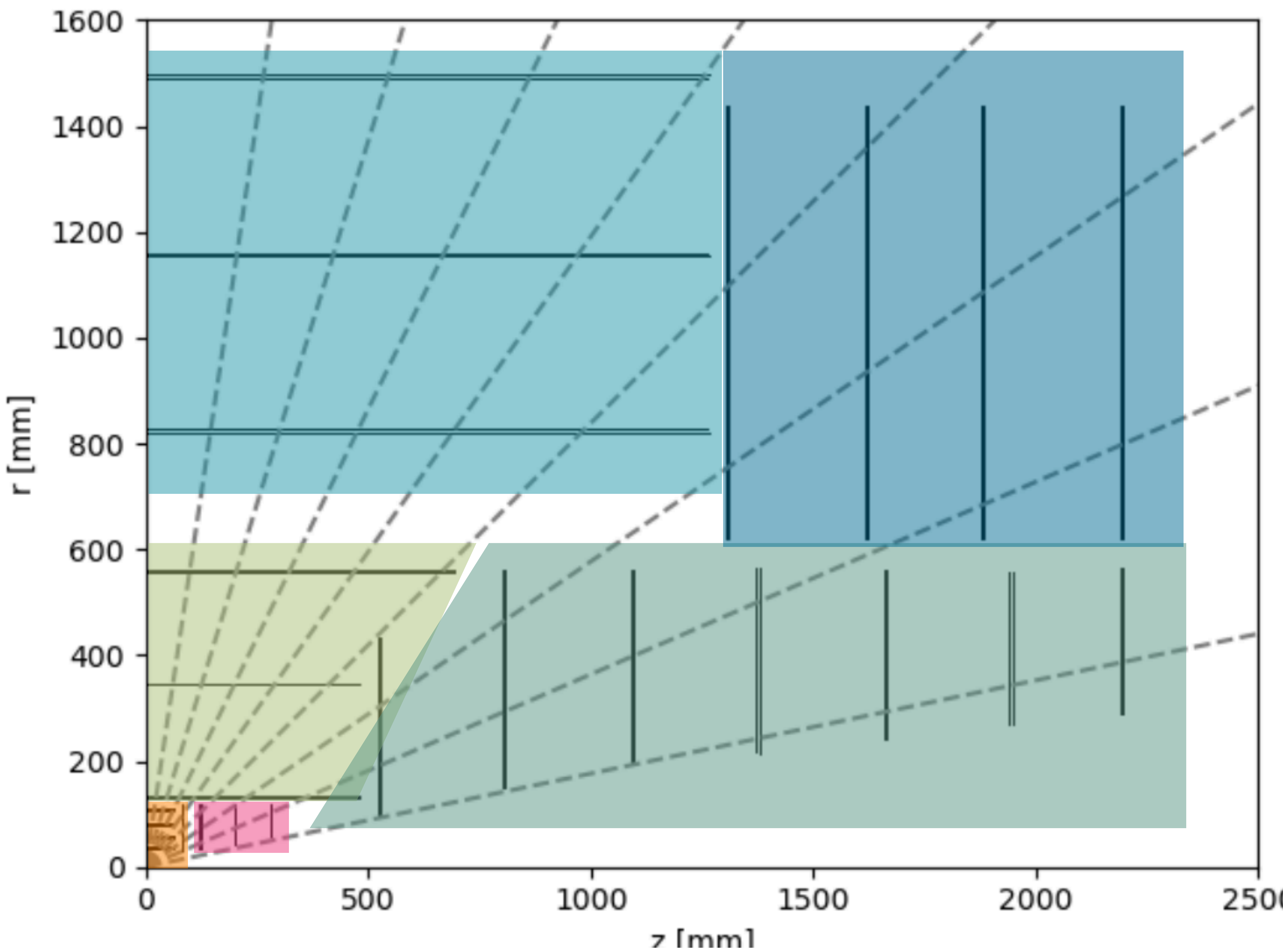
O(100) hits/cm² ⟶

need O(10k) pixels/cm² for 1% occupancy (100 μm pitch)

Detector Performance Report

Biggest challenge: tracker





even with this, still see huge flux in first two layers:

$$l_x \times l_y = \left(\frac{o_{\text{max}}}{n_{\text{hits}}}\right) \text{cm}^2 = 100{,}000\ \mu m^2$$

O(10) hits/cm² →

need O(1k) pixels/cm² for

1% occupancy (300 μm pitch)

Detector Performance Report

Biggest challenge: tracker

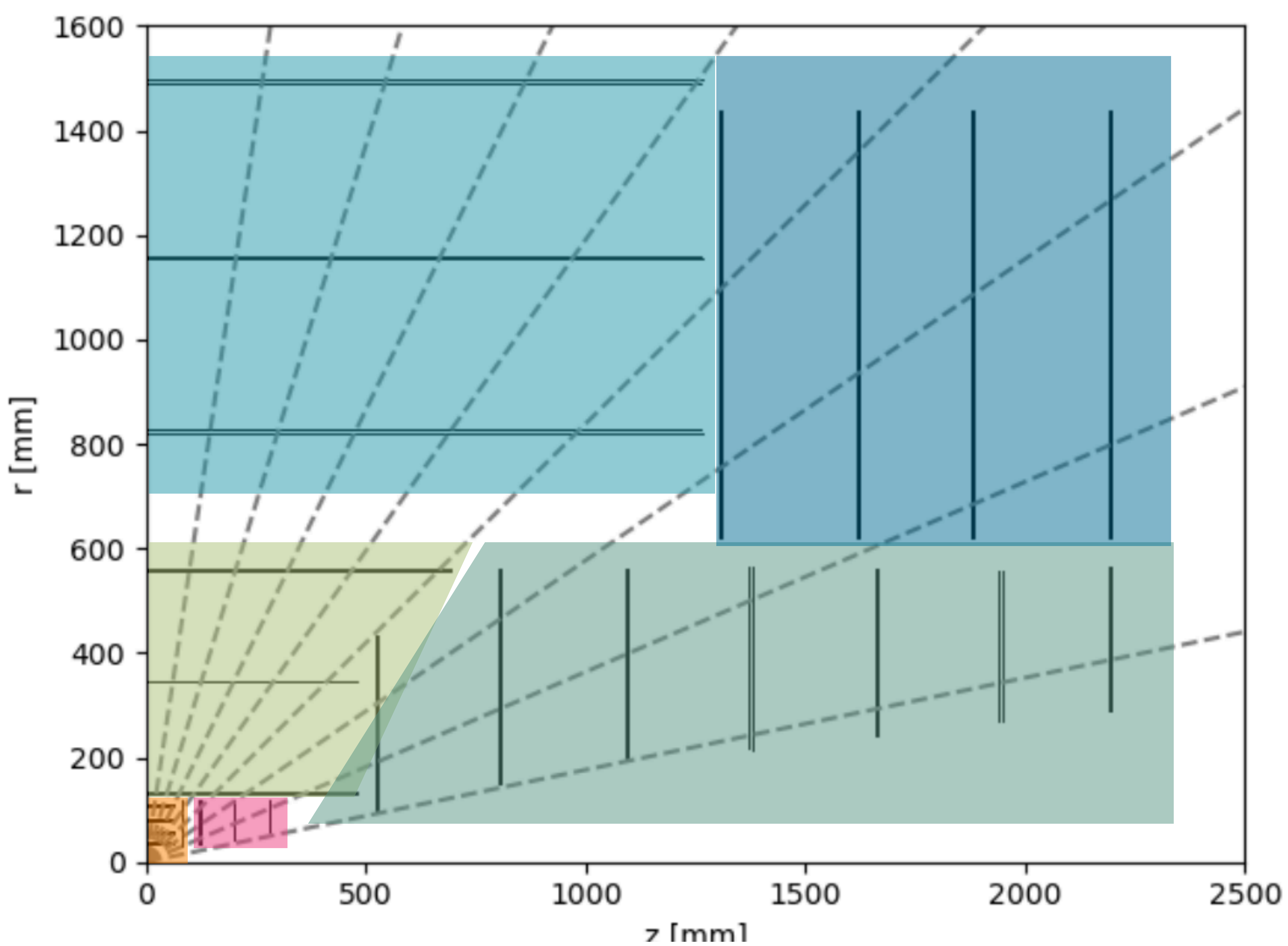
in practice, also optimize for resolution in phi direction

	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

$= 625\ \mu m^2$ (60% more)

$= 50{,}000\ \mu m^2$ (20% more)

$= 500{,}000\ \mu m^2$ (20% more)



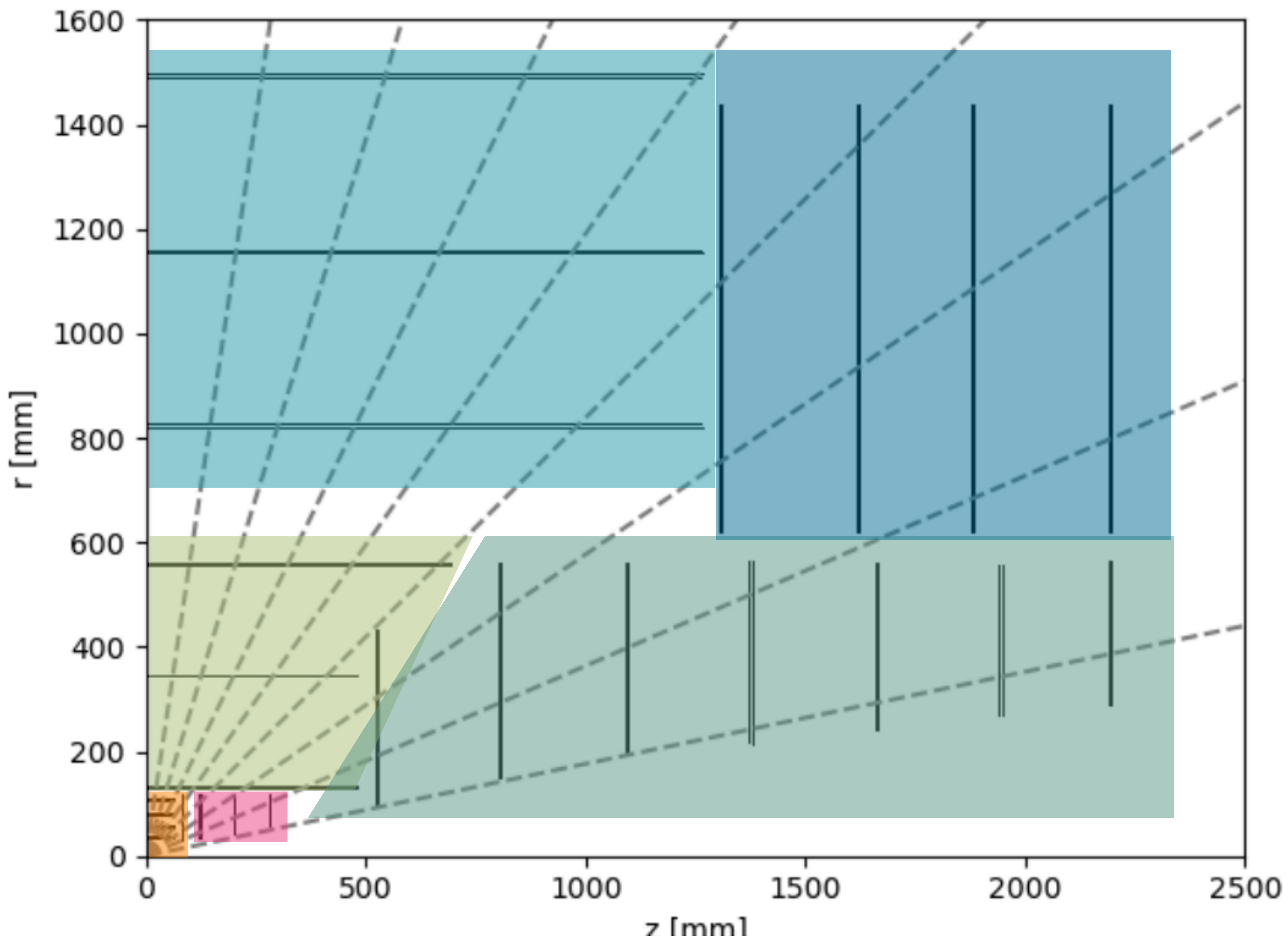
Detector Performance Report

Biggest challenge: tracker

in practice, also optimize for resolution in phi direction

	Vertex Detector	**Inner Tracker**	**Outer Tracker**
Cell type	pixels	macropixels	microstrips
Cell Size	25 μm × 25 μm	50 μm × 1 mm	50 μm × 10 mm
Sensor Thickness	50 μm	100 μm	100 μm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 μm × 5 μm	7 μm × 90 μm	7 μm × 90 μm

ATLAS ITk Layer	**ITk Hit Density** [mm^2]	**MCD Equiv. Hit Density** [mm^2]
Pixel Layer 0	0.643	3.68
Pixel Layer 1	0.022	0.51
Strips Layer 1	0.003	0.03

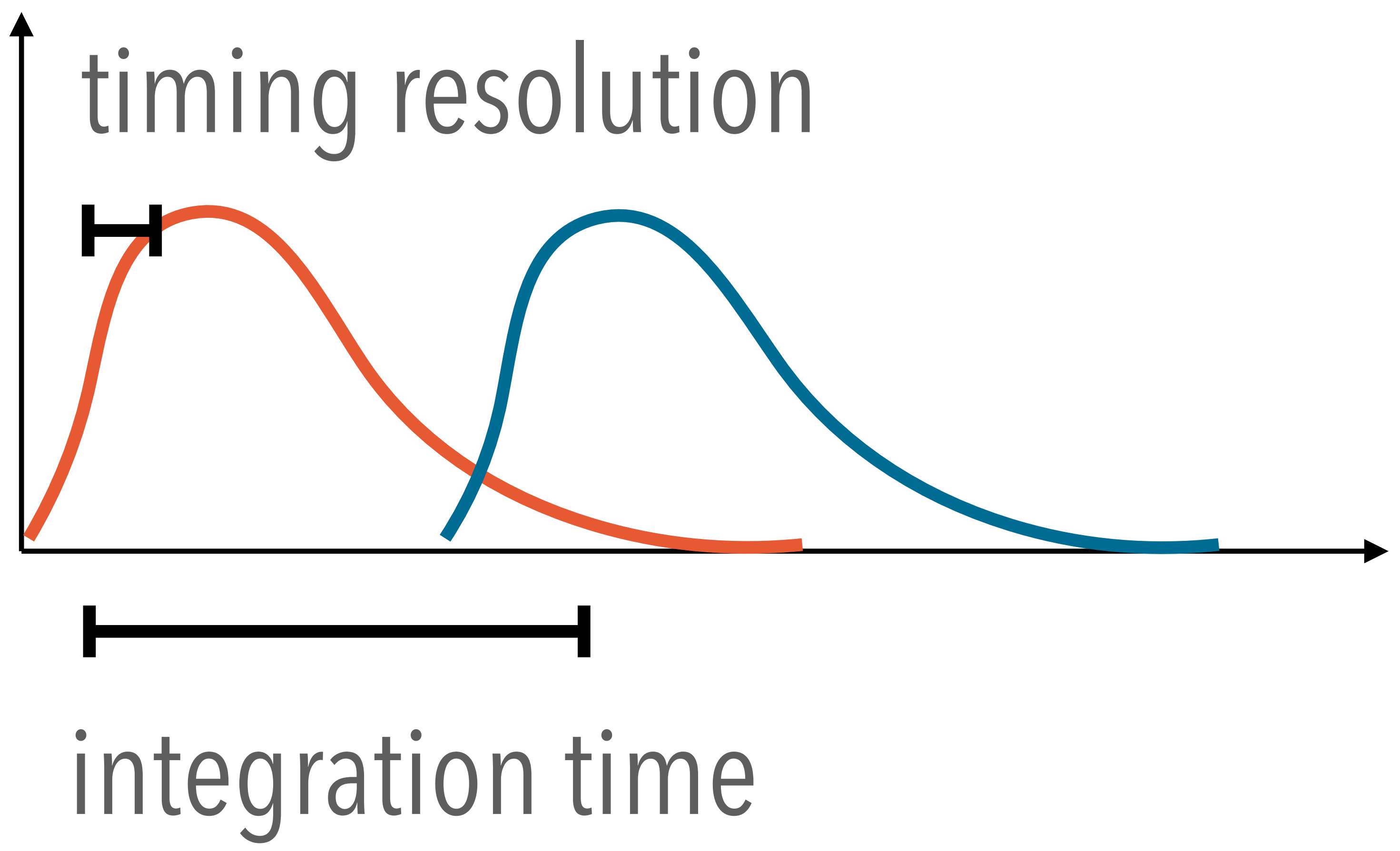


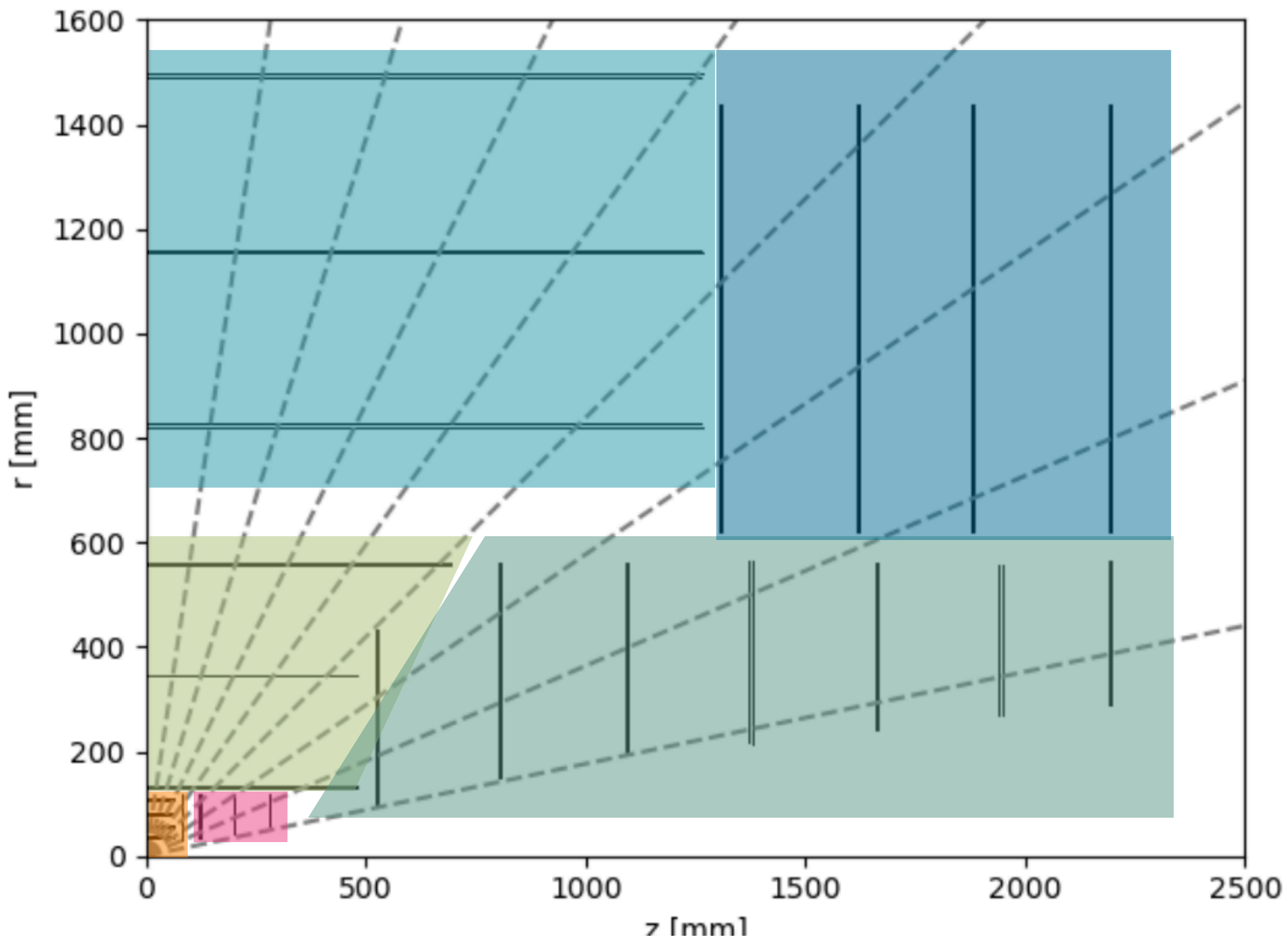
~10x hit density, but ~1/1000 times the bunch crossing rate

compared to1MHz HL-LHC readout, around half the link rate

Detector Performance Report

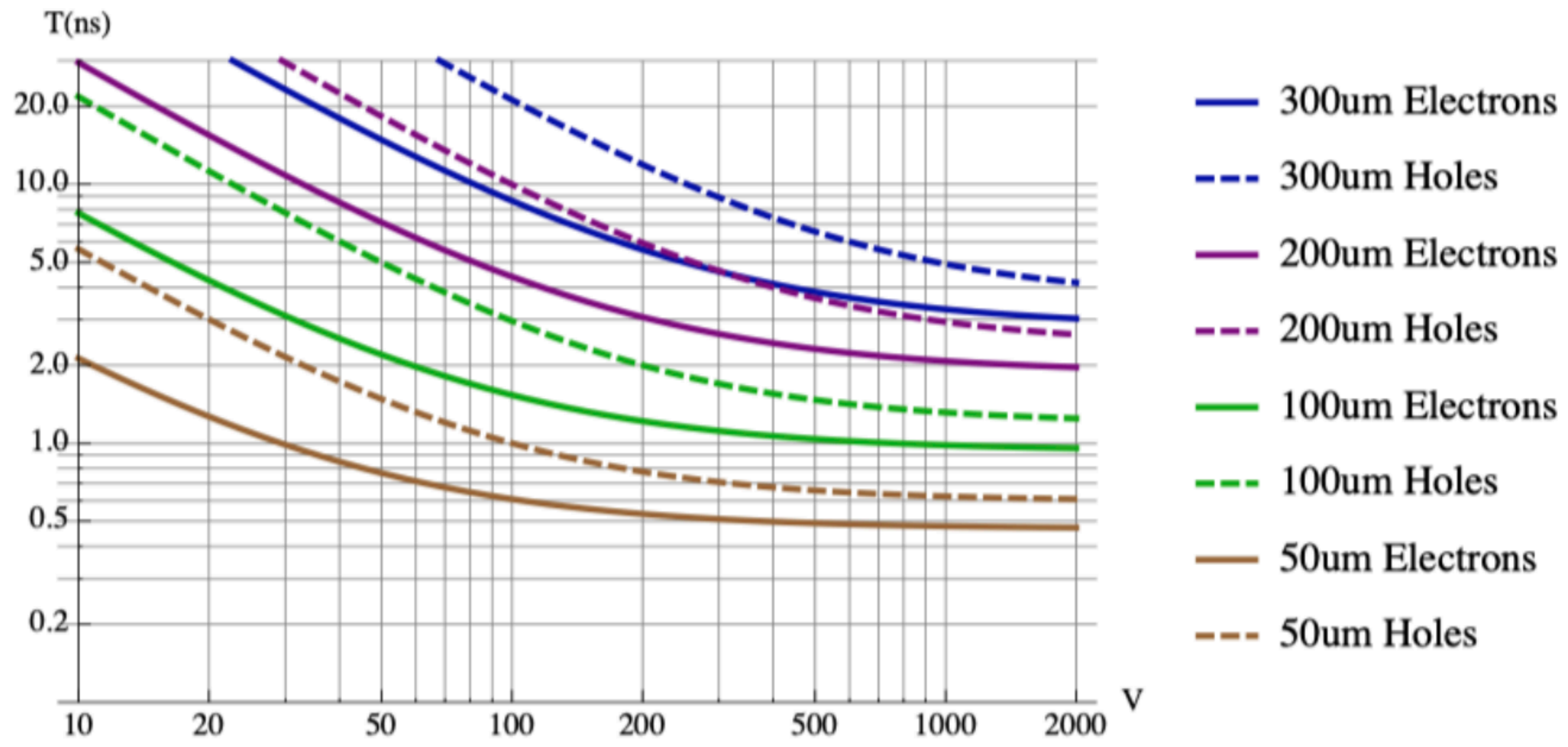
Biggest challenge: tracker

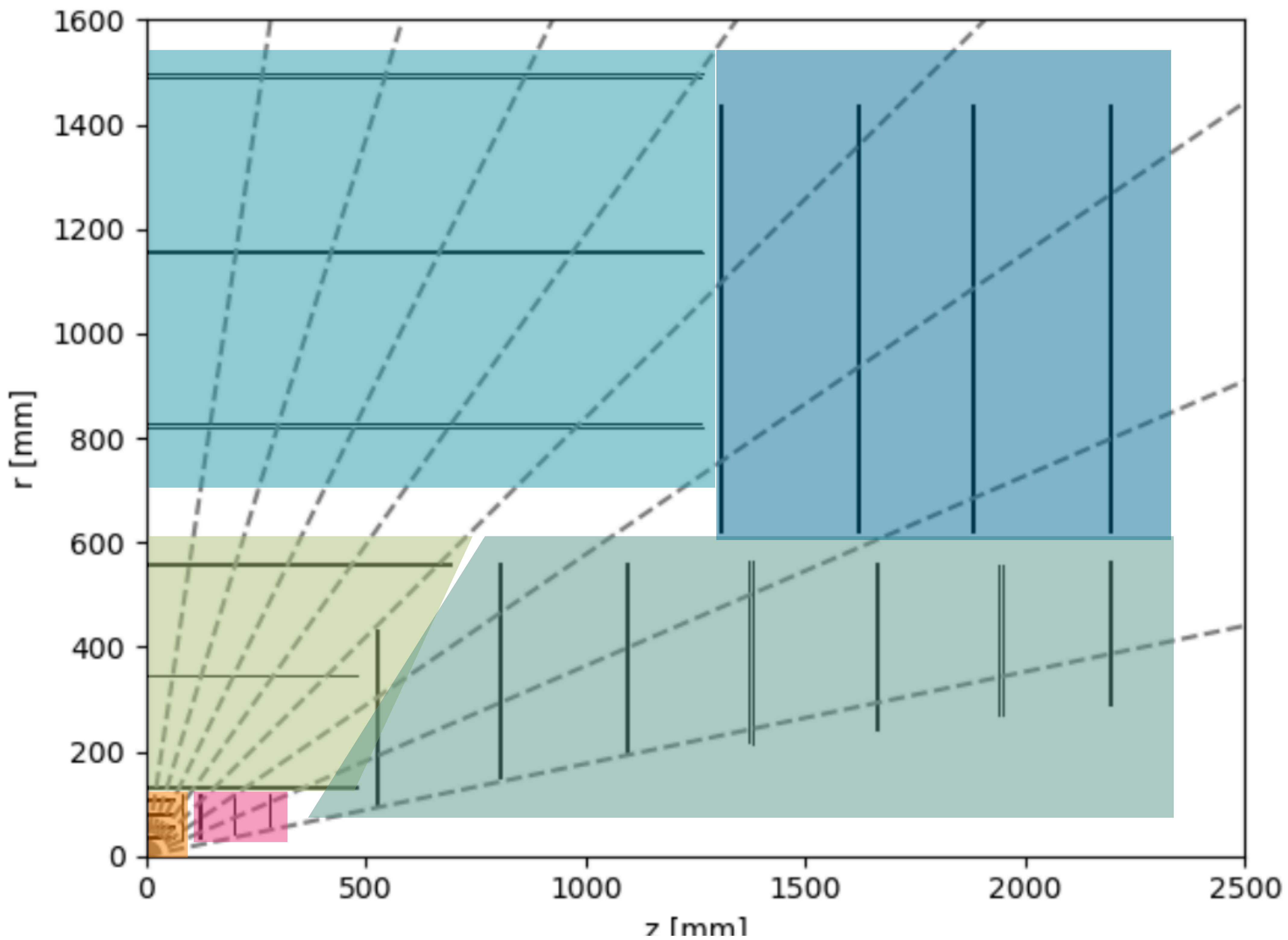




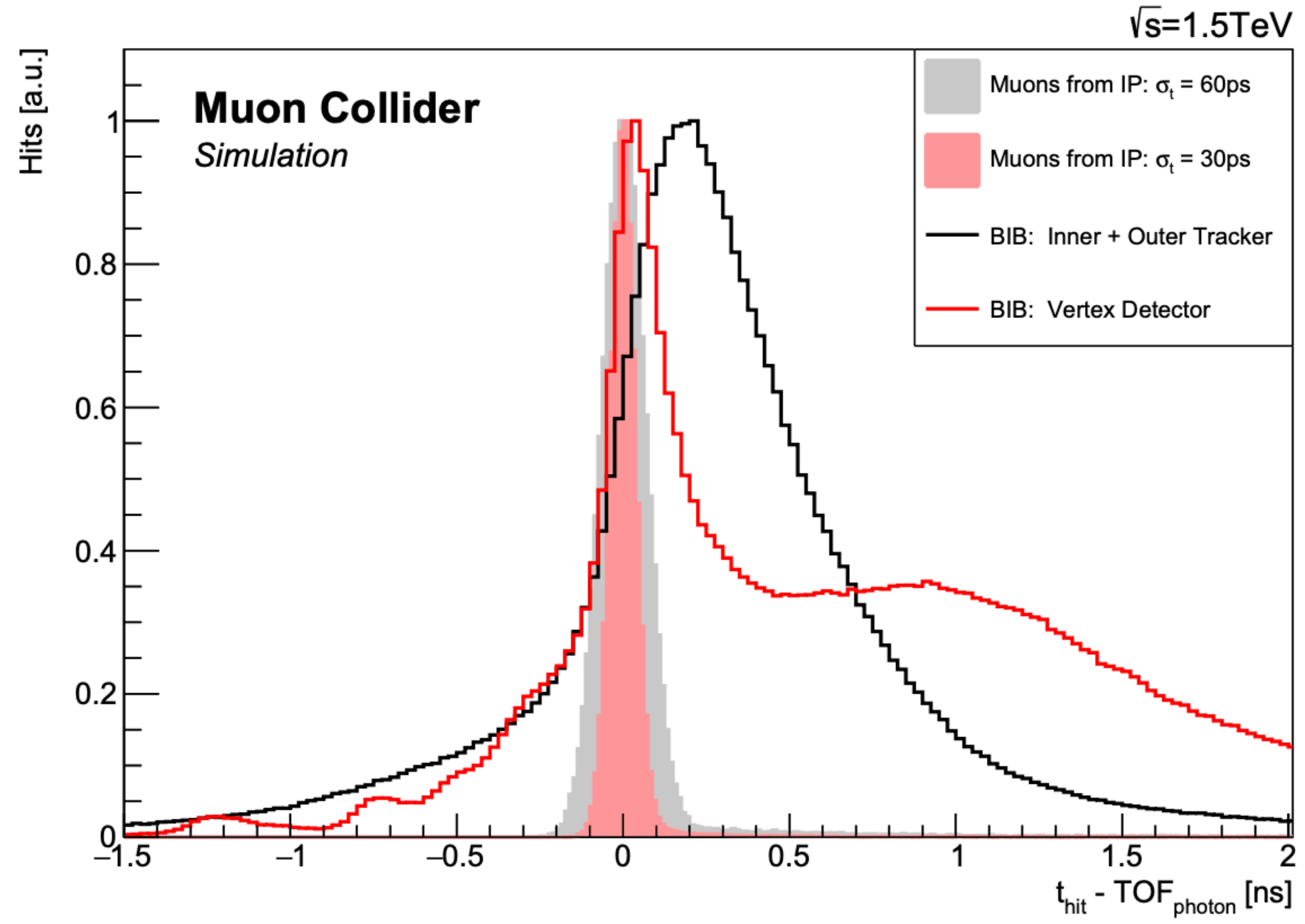
only get 1% occupancy if we are talking about O(ns) integration

Biggest challenge: tracker





expanding the timing window introduces a lot more BIB



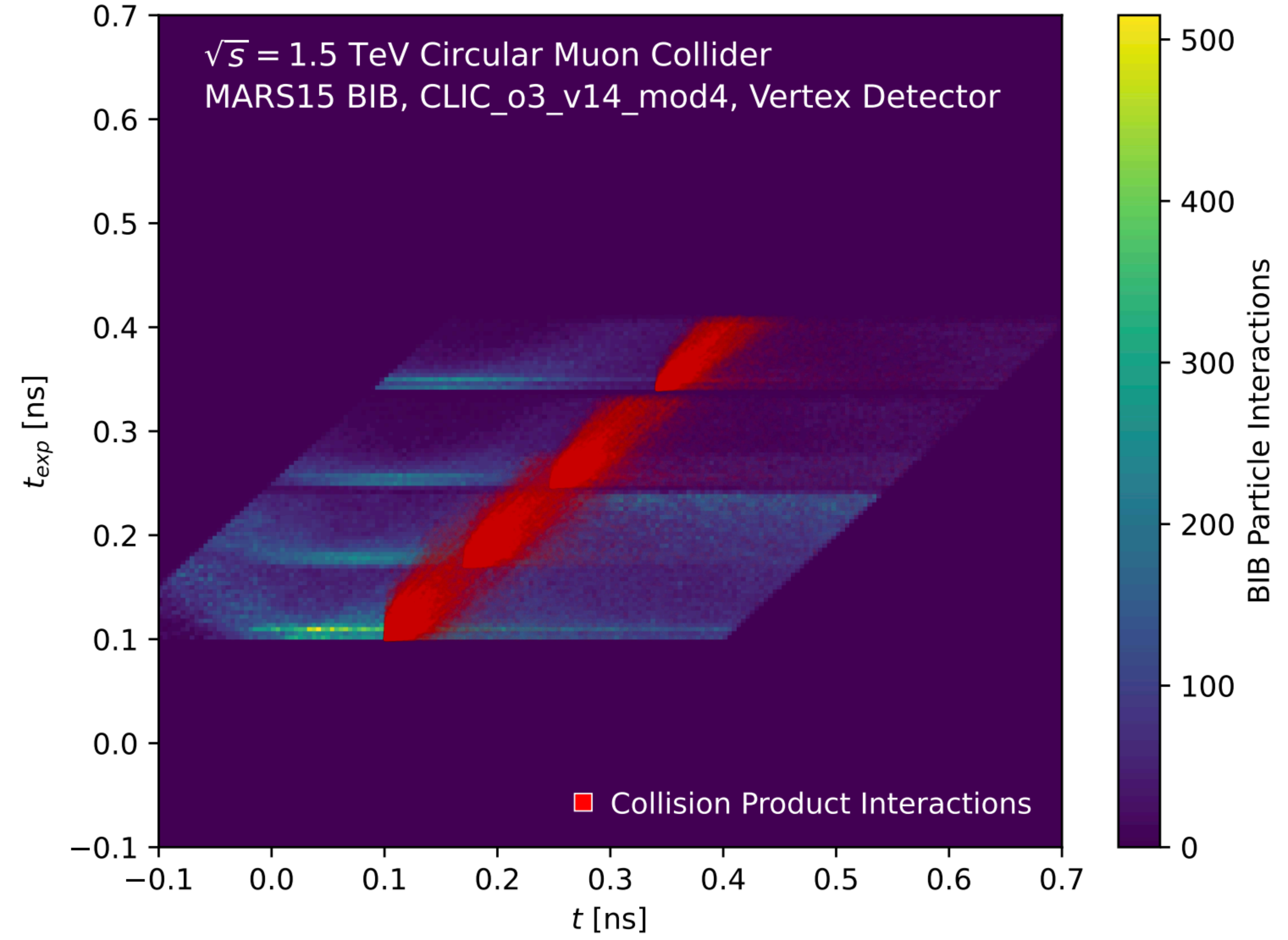
only get 1% occupancy if we are talking about O(ns) integration

Detector Performance Report W. Riegler

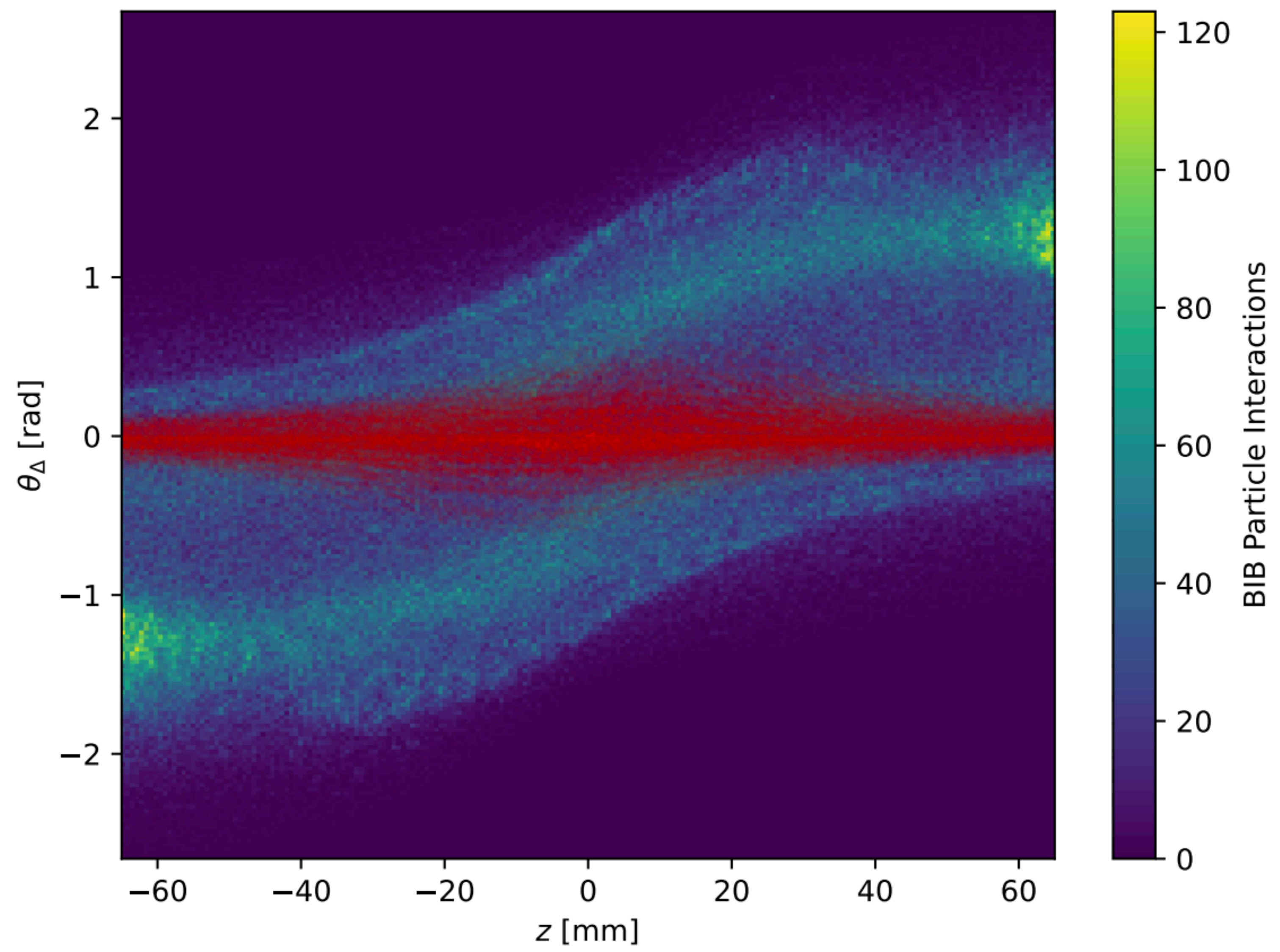
Biggest challenge: tracker

once signals are processed,
two main features
to reject BIB hits on-detector

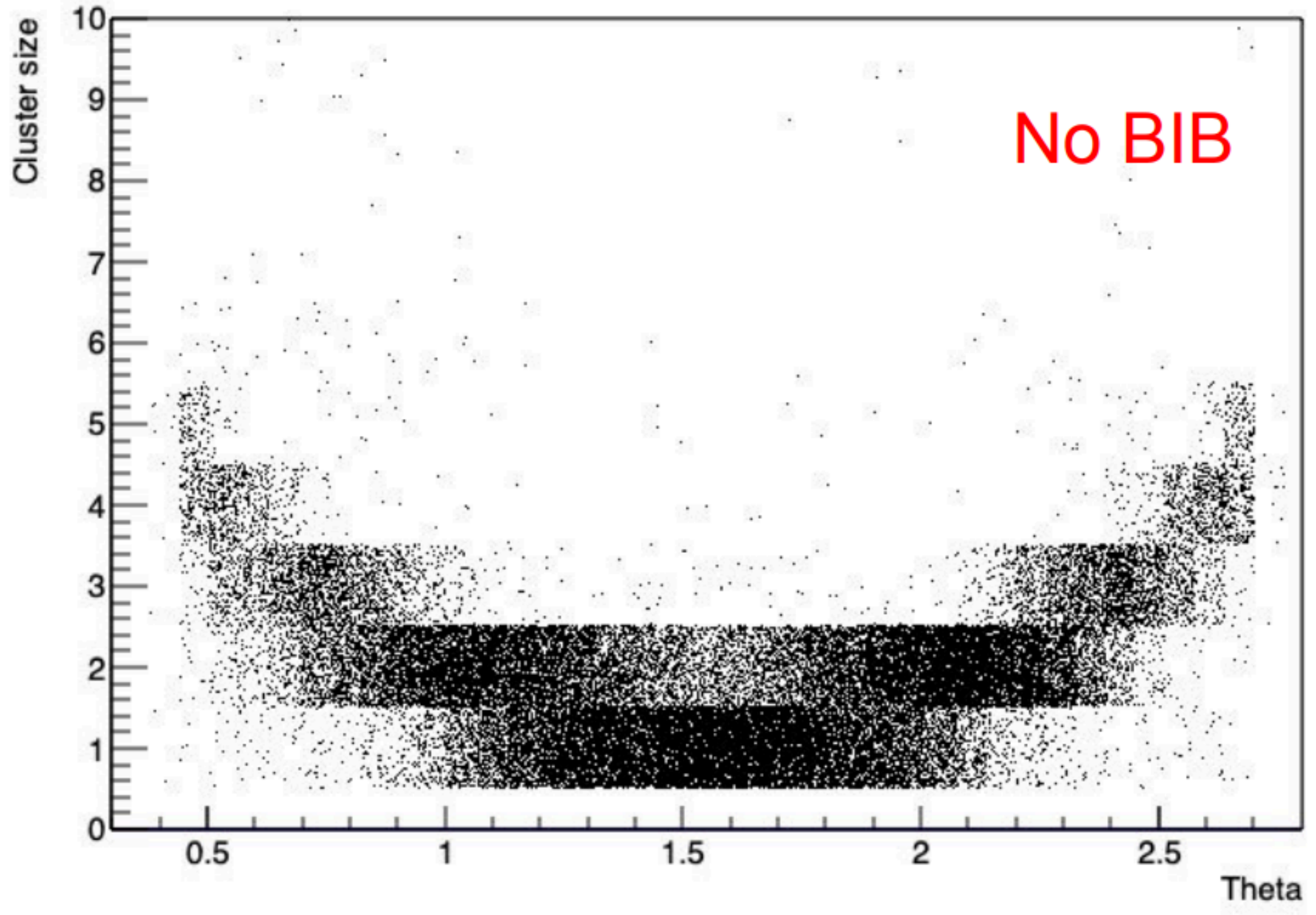
precision timing



angular features



measurements using double layers

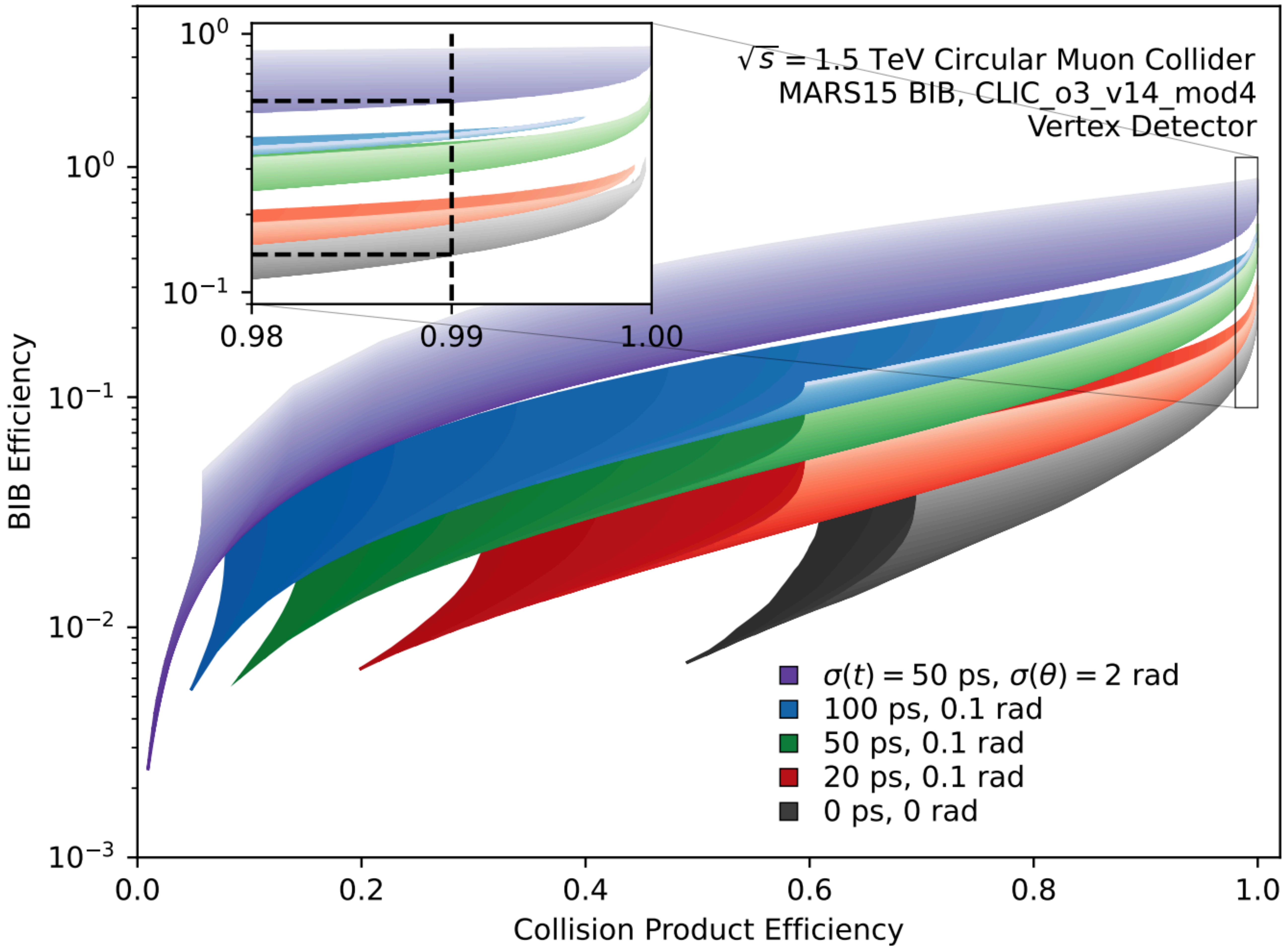


cluster sizes

D. Ally et. al.   N. Bruhwiler, S. Pagan Griso

Biggest challenge: tracker

once signals are processed,
two main features
to reject BIB hits on-detector



combine for OoM reduction in vertex detector
(2 OoM without beamspot considerations)

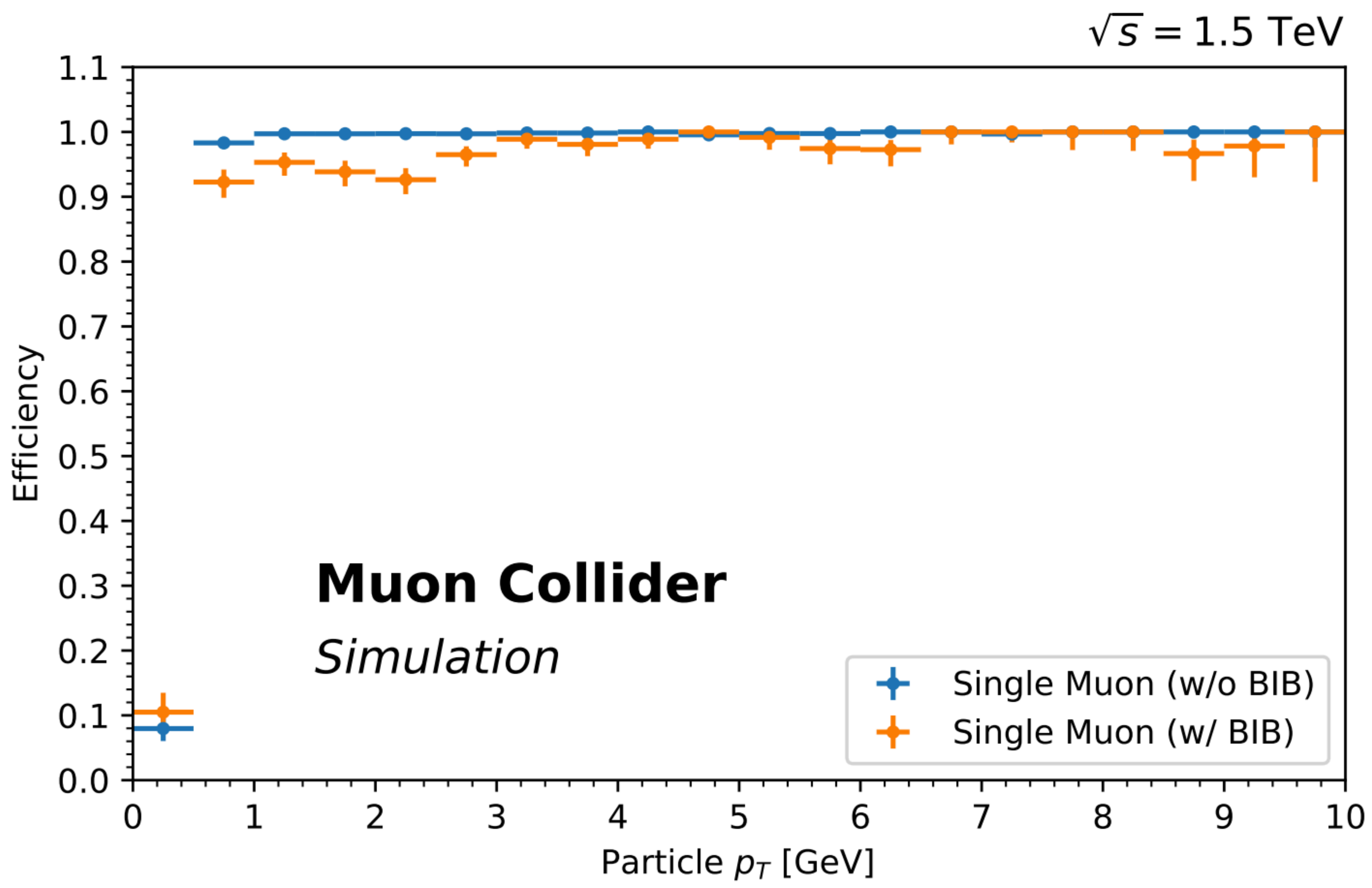
D. Ally et. al.

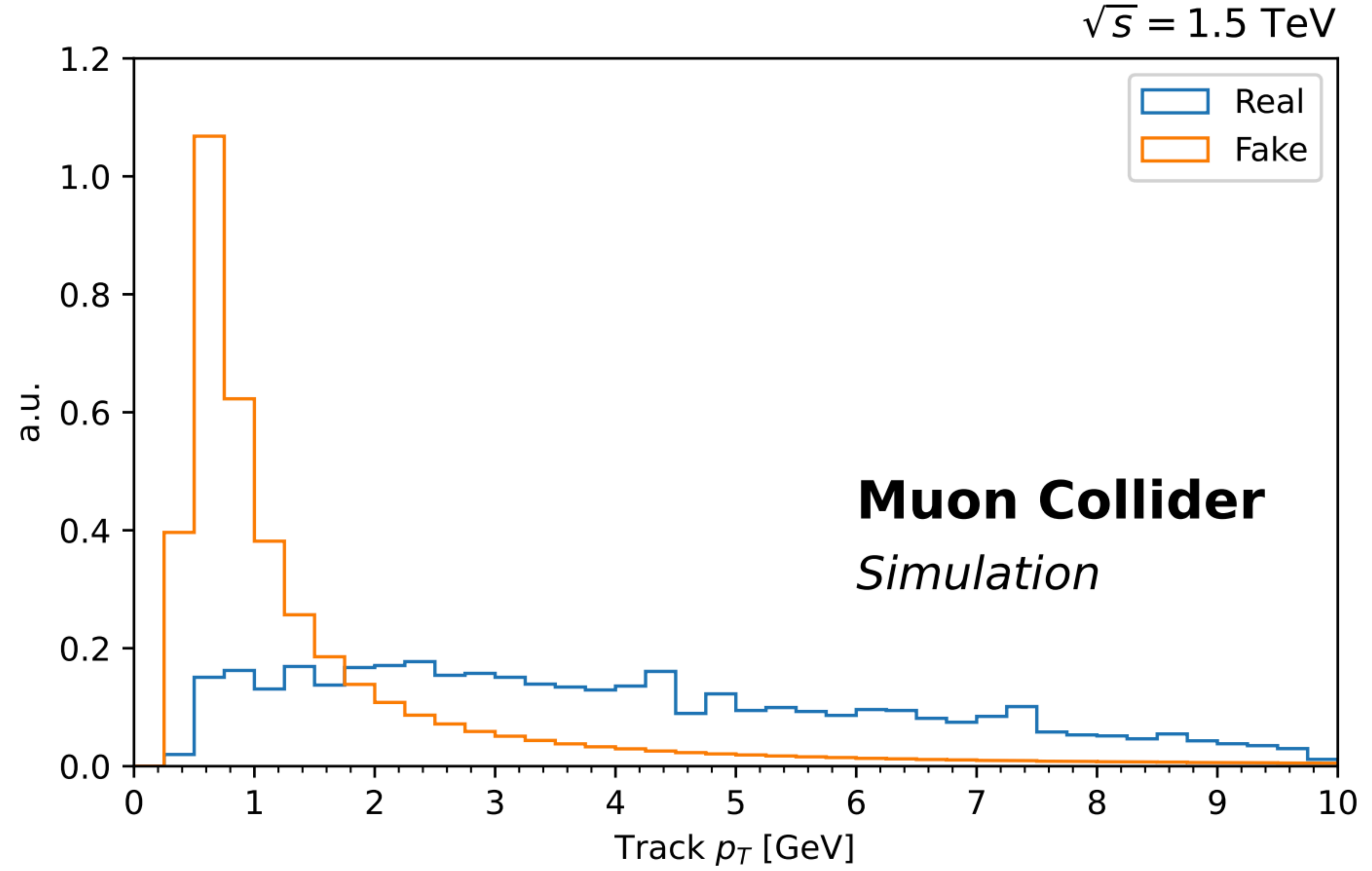
Biggest challenge: tracker

once reduced to a level that can be reasonably read out, tracking makes it possible to reject additional BIB

~100,000 fake tracks per event, but largely low-pT, fewer hits. can be drastically reduced with quality handles

find examples of this applied to b-tagging and analyses here





Detector Performance Report

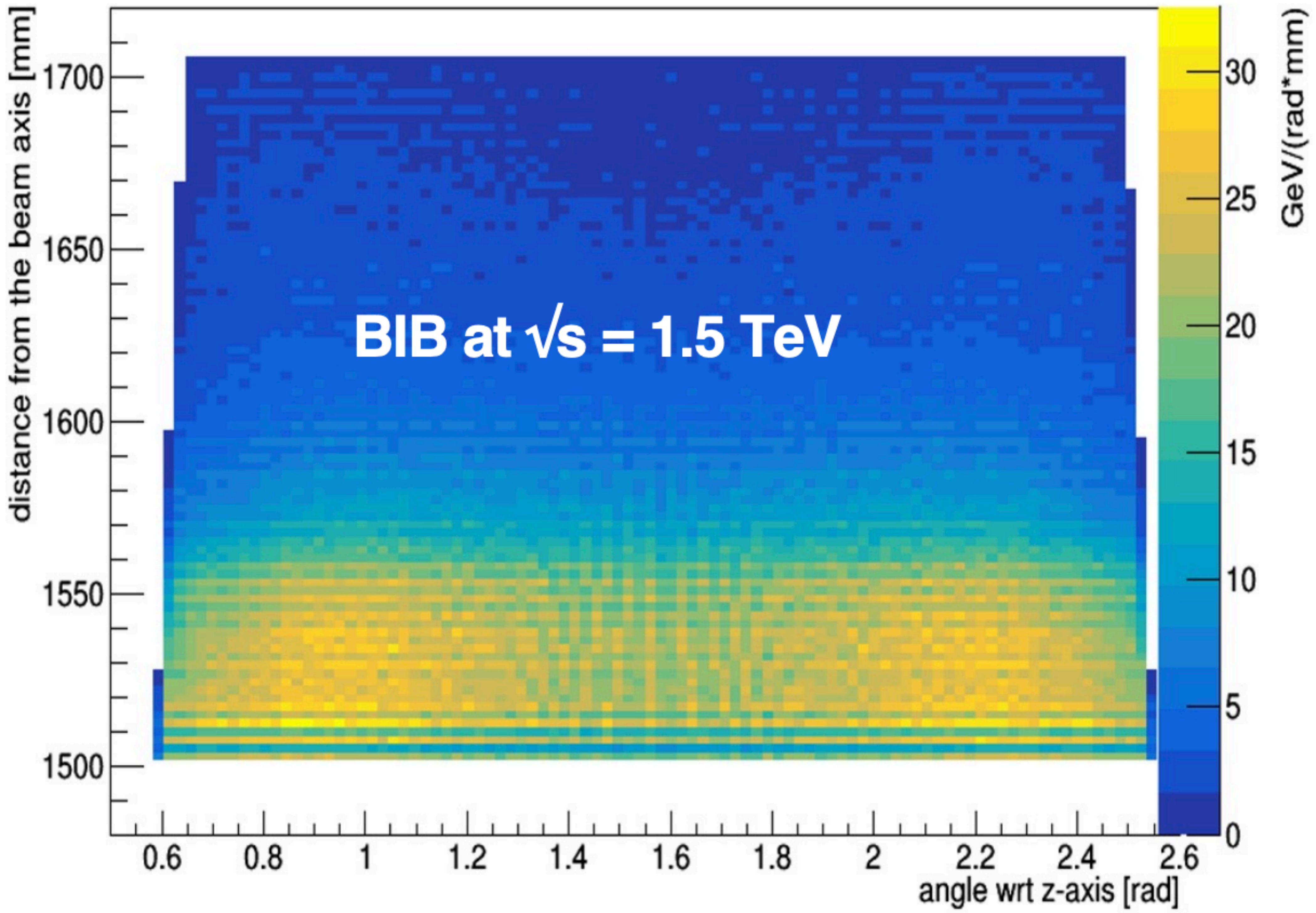
K. Krizka

BIB in the calorimeters

advantages: response is proportional to energy, so low energy particles have less impact

large R means much smaller particle flux

disadvantage: typically lower granularity and longer readout times means much more susceptible to signal contamination from BIB



BIB in the calorimeters

Find about 20% more total energy in calorimeter than for HL-LHC (10 ns time window)

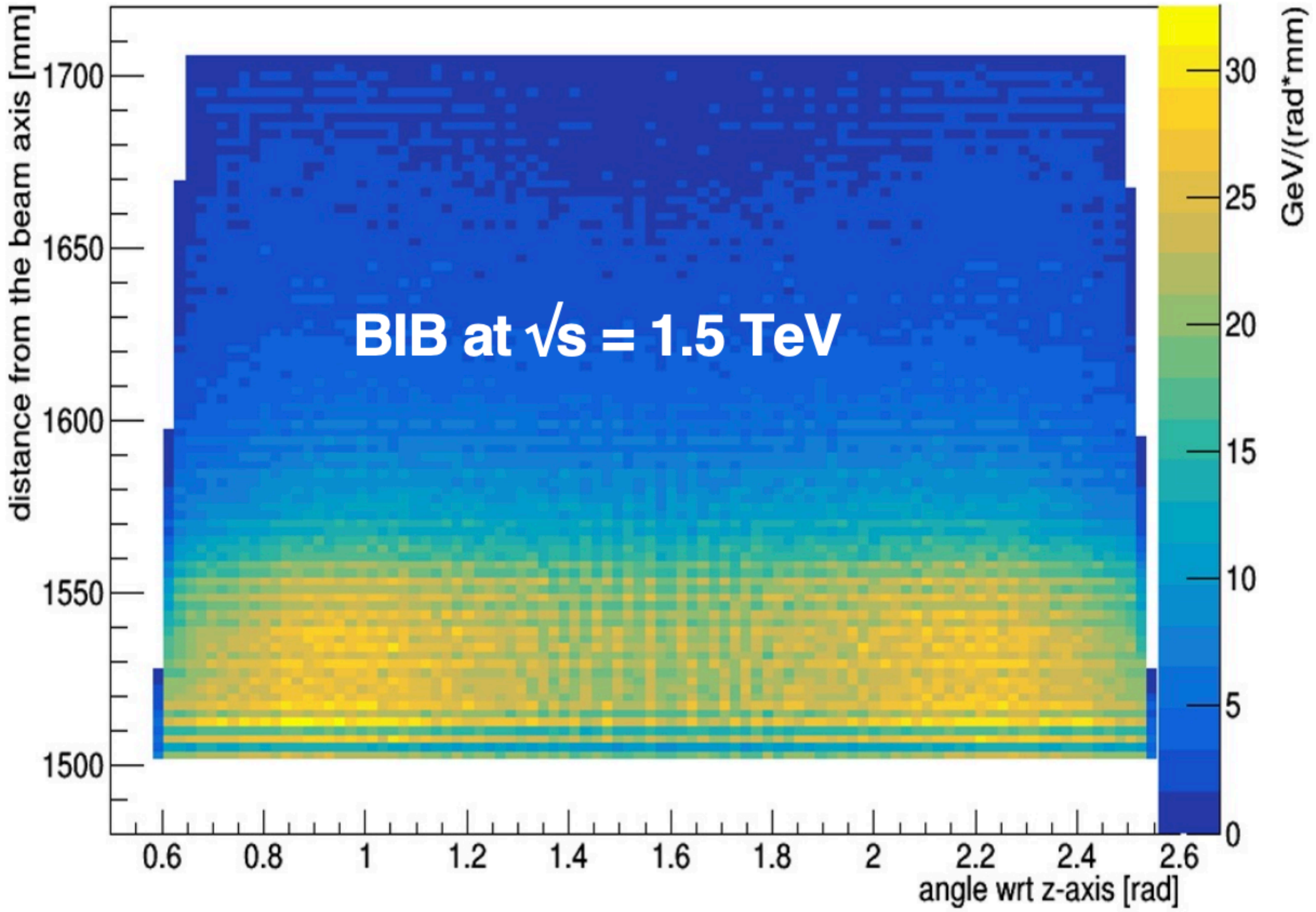
From the plot on right:

30 GeV/rad*mm = 500 MeV in 5x5 mm^2 @ 1.5 m

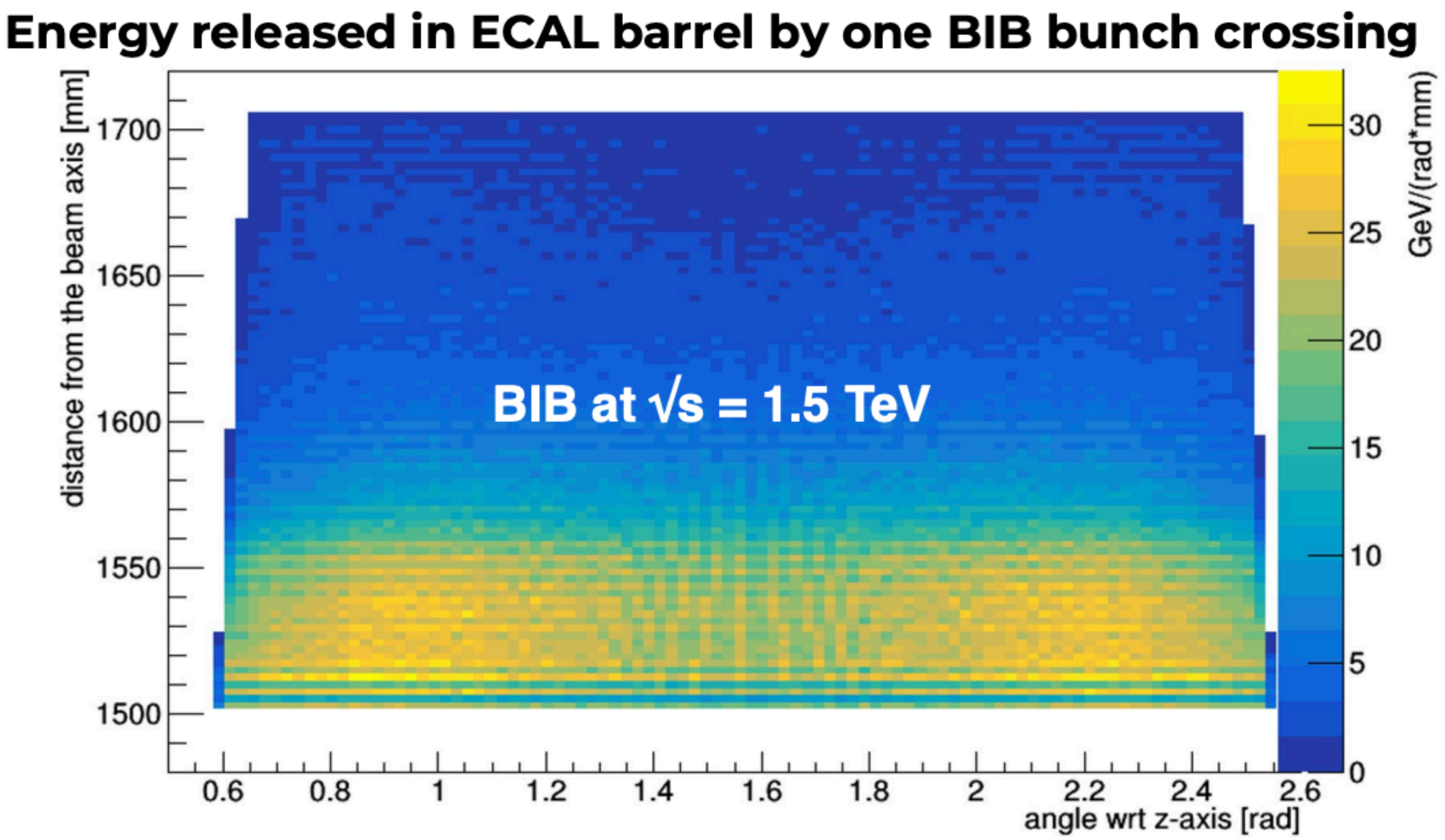
10 GeV/rad*mm = 150 MeV in 5x5 mm^2 @ 1.6 m

1 GeV/rad*mm = 15 MeV in 5x5 mm^2 @ 1.7 m

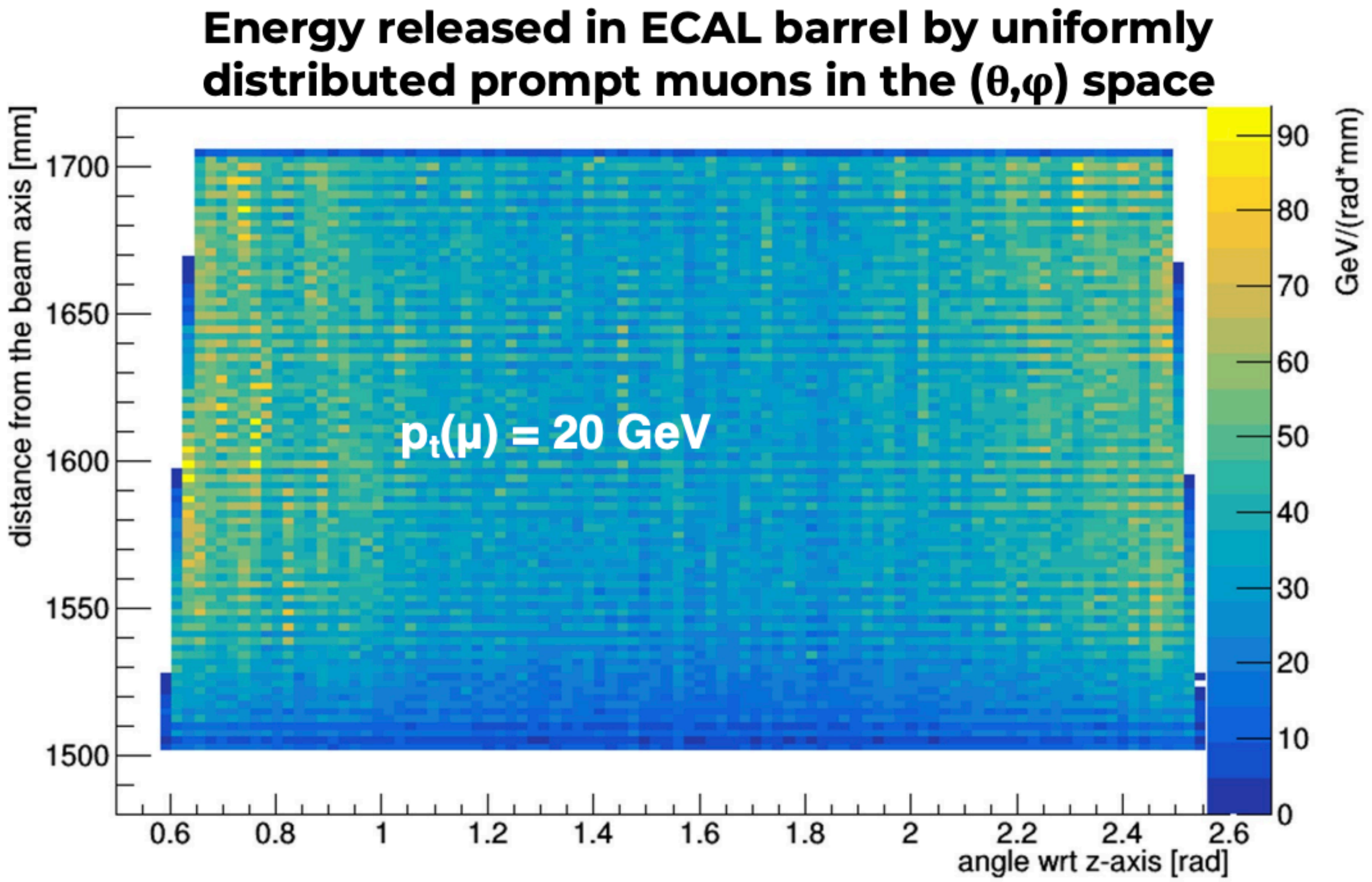
greatly reduced by the end of the ECAL



BIB in the calorimeters



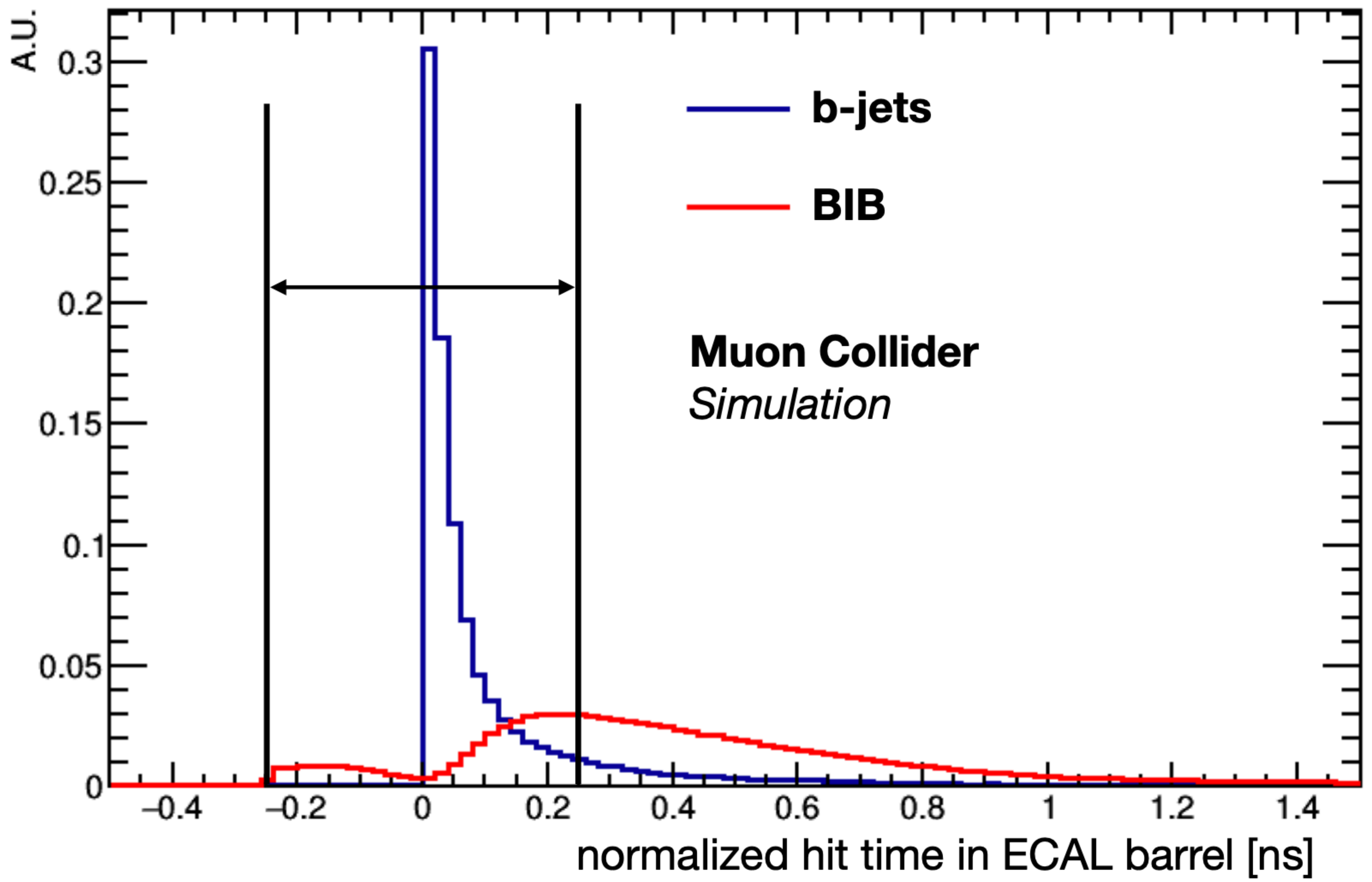
BIB very concentrated at small R, reduced drastically by the end of the ECal



Signal is distinct from BIB, with distributions extending to large R

I. Sarra

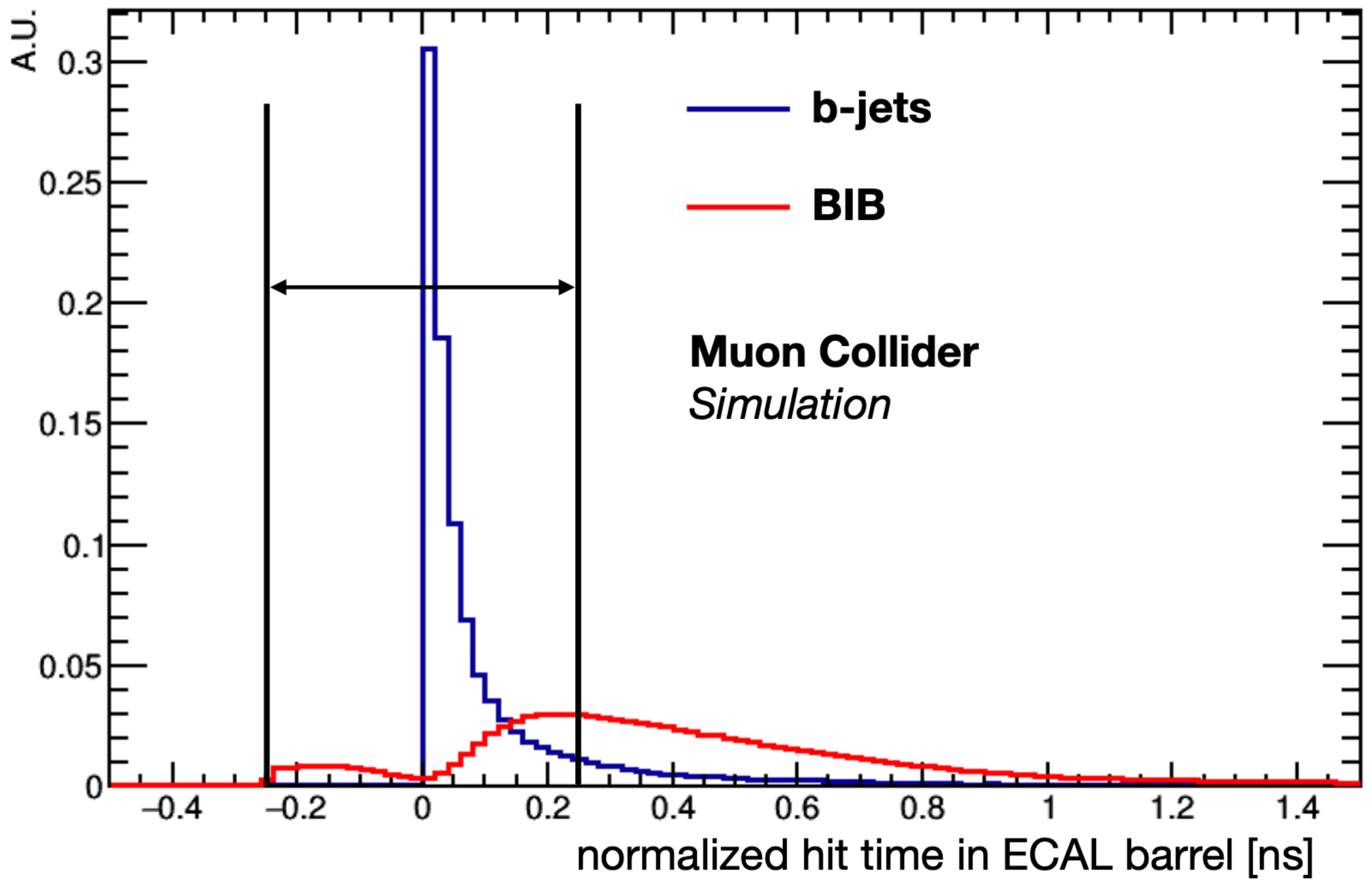
BIB in the calorimeters



reduction of BIB possible with timing windows

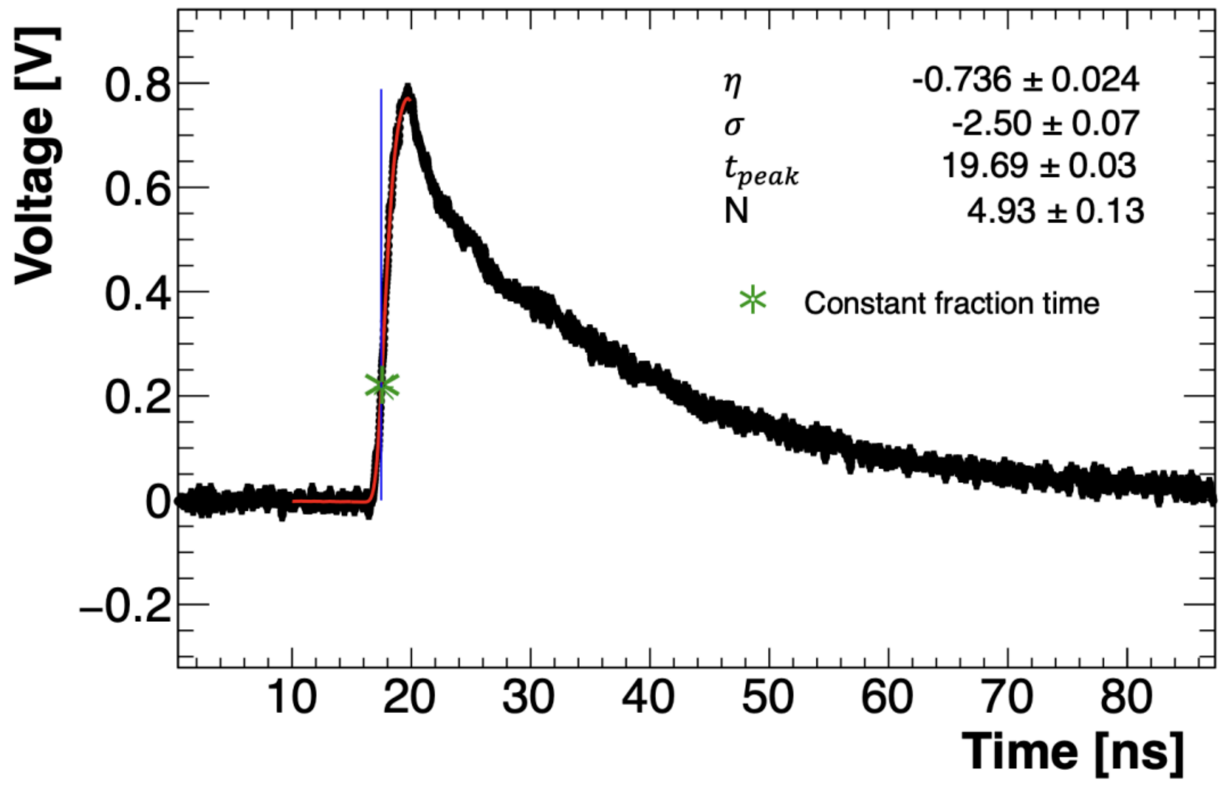
resolution of ~100 ps needed

BIB in the calorimeters

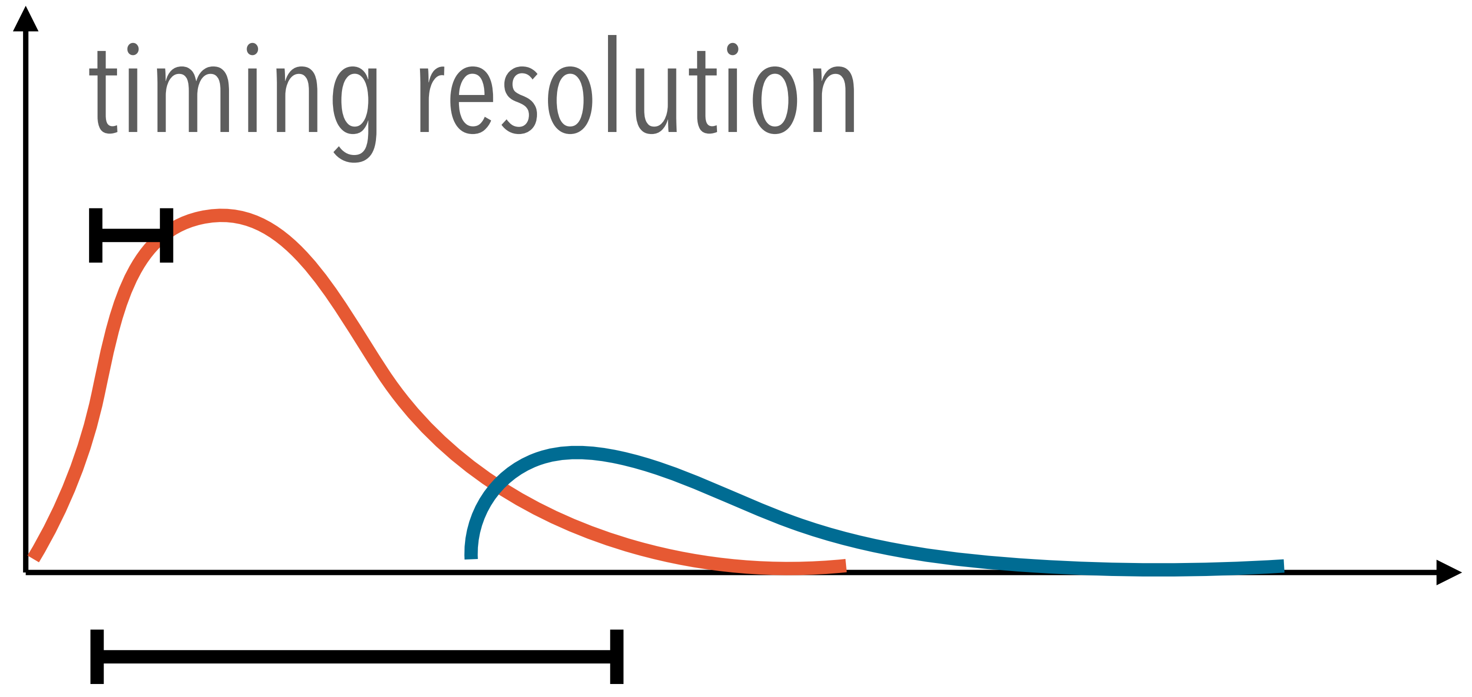


as with tracker, must consider integration time

current integration times ~100 ns, CRILIN could ~half that, silicon readout could reduce dramatically



BIB hits much lower energy, may be able to subtract effects from tail of signal



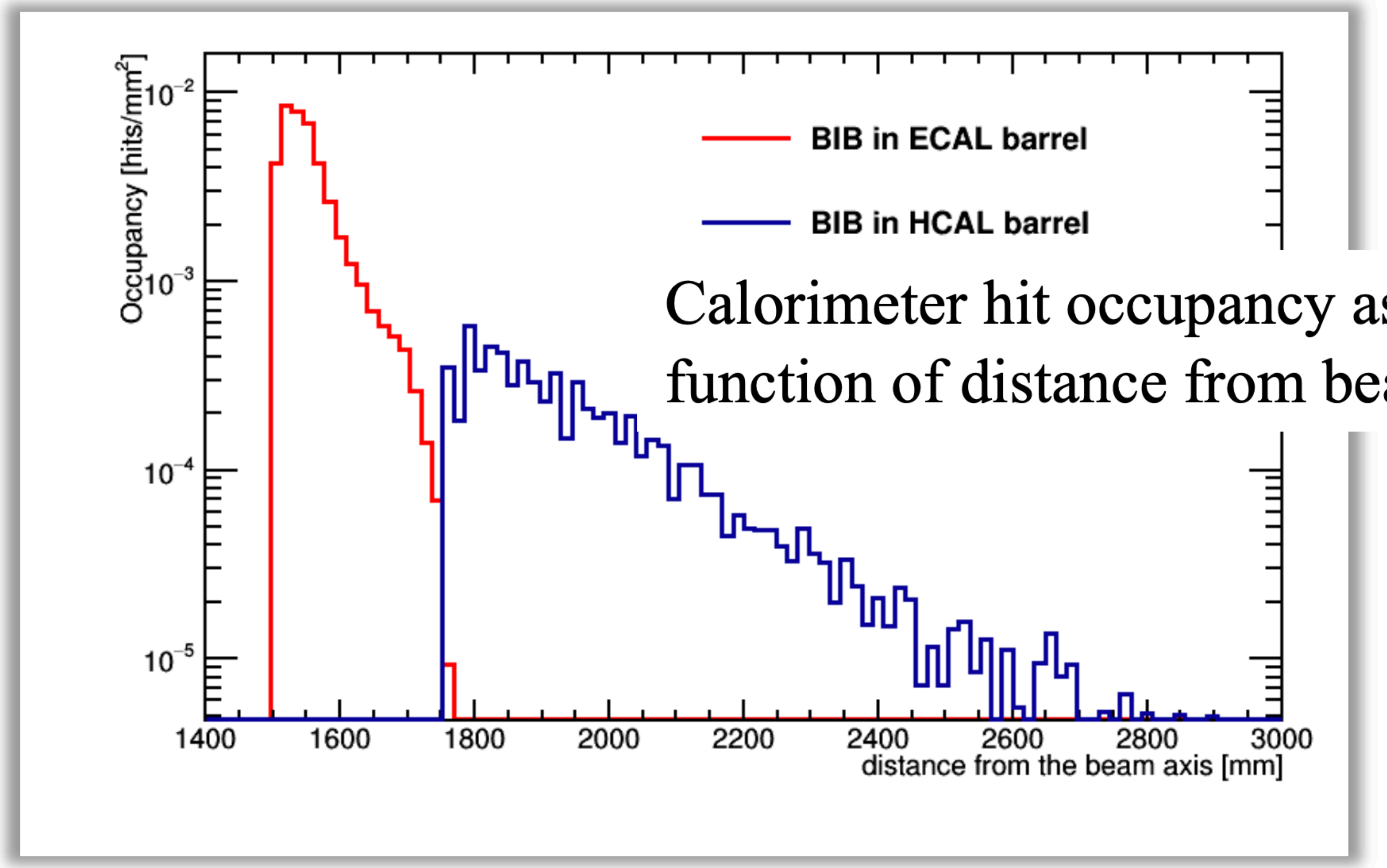
Detector Performance Report S. Ceravolo et. al.

BIB in the calorimeters

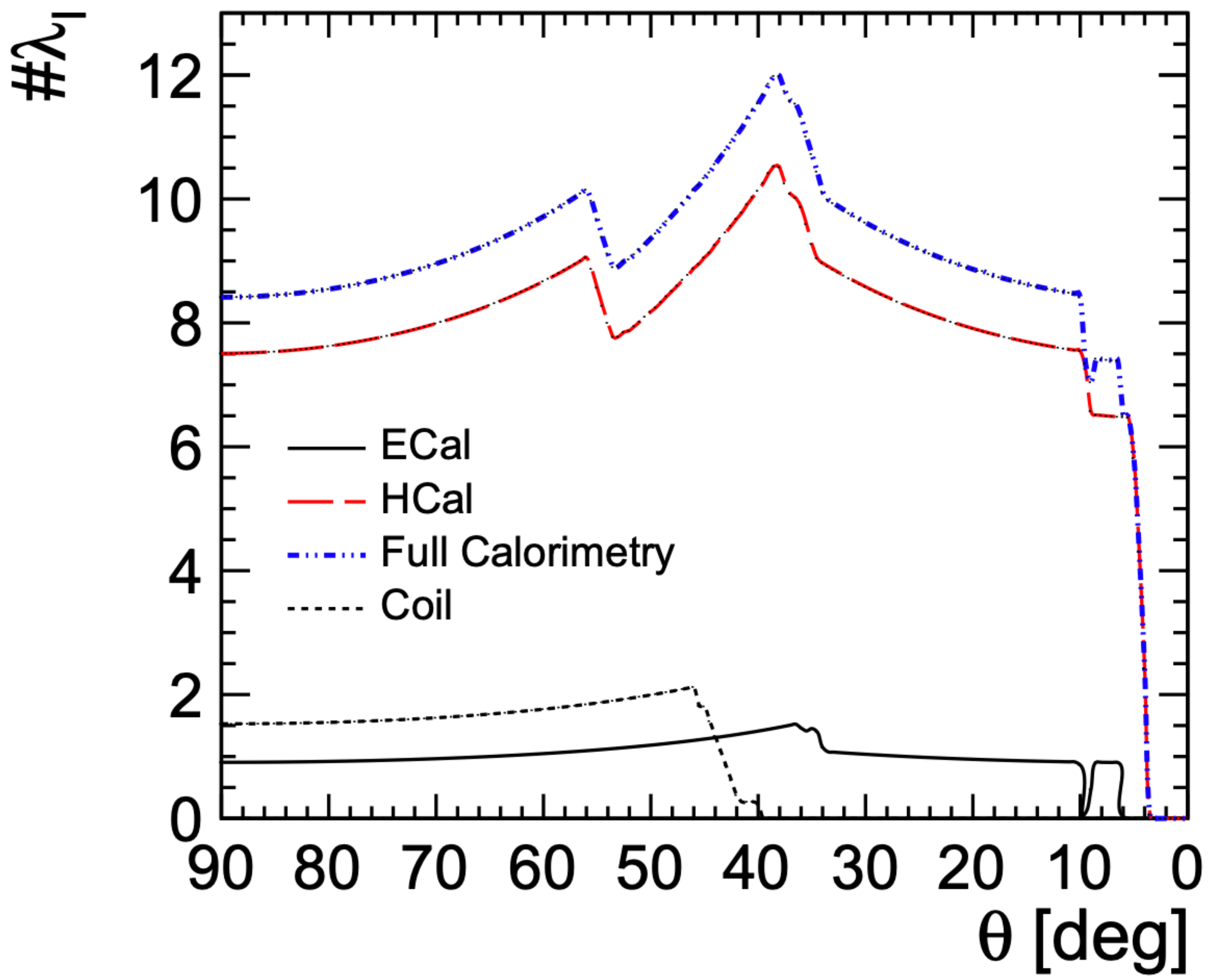
Current detector design taken from CLIC

ECAL: 5x5 mm² silicon sensor pads alternating with tungsten plates, resolution $10\,\%/\sqrt{E}$ for photons

HCAL: 30x30 mm² scintillating tiles alternating with steel absorbers, $35\,\%/\sqrt{E}$ for jets



Calorimeter hit occupancy as function of distance from beam axis



Detector Performance Report CLIC

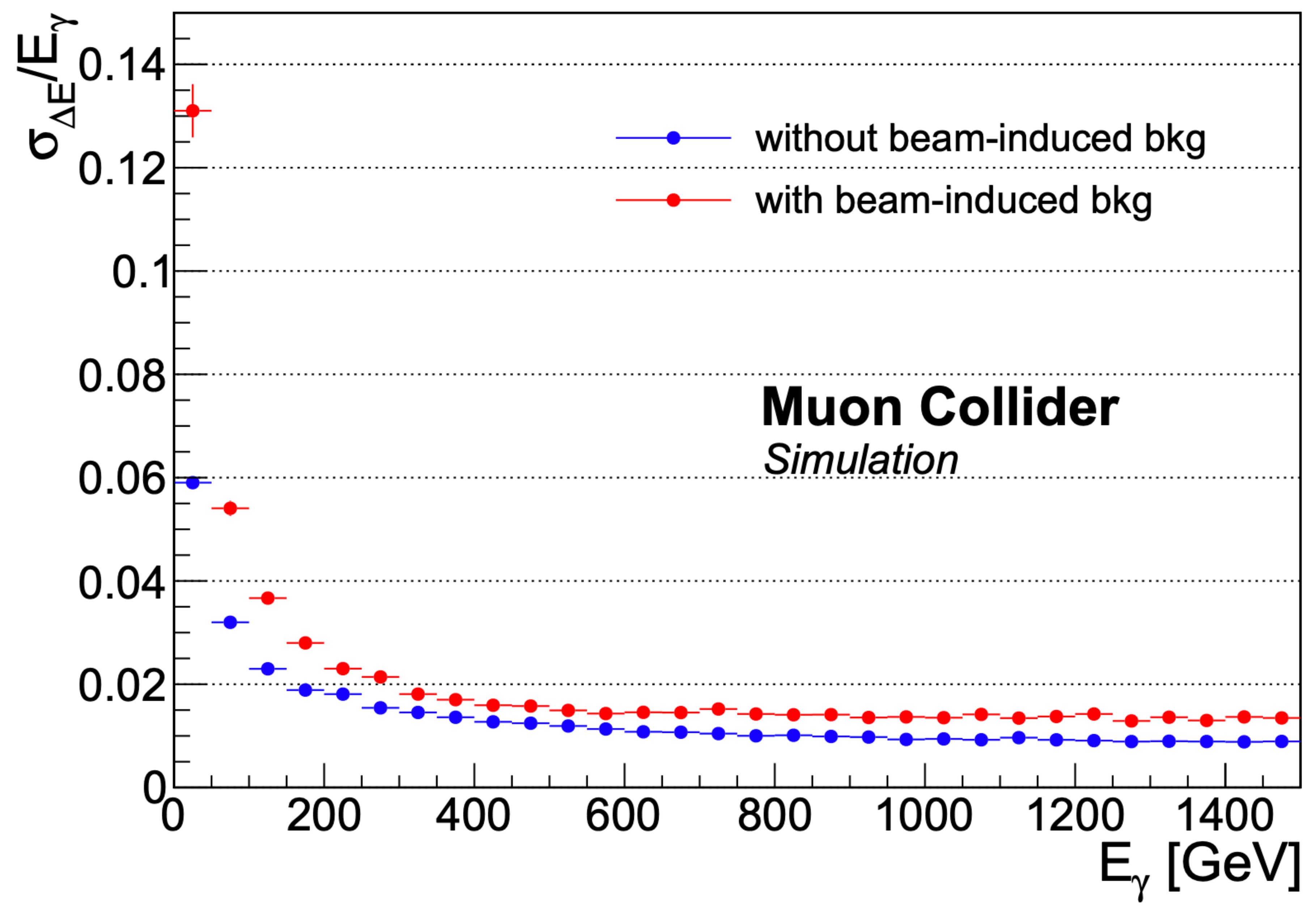
BIB in the calorimeters

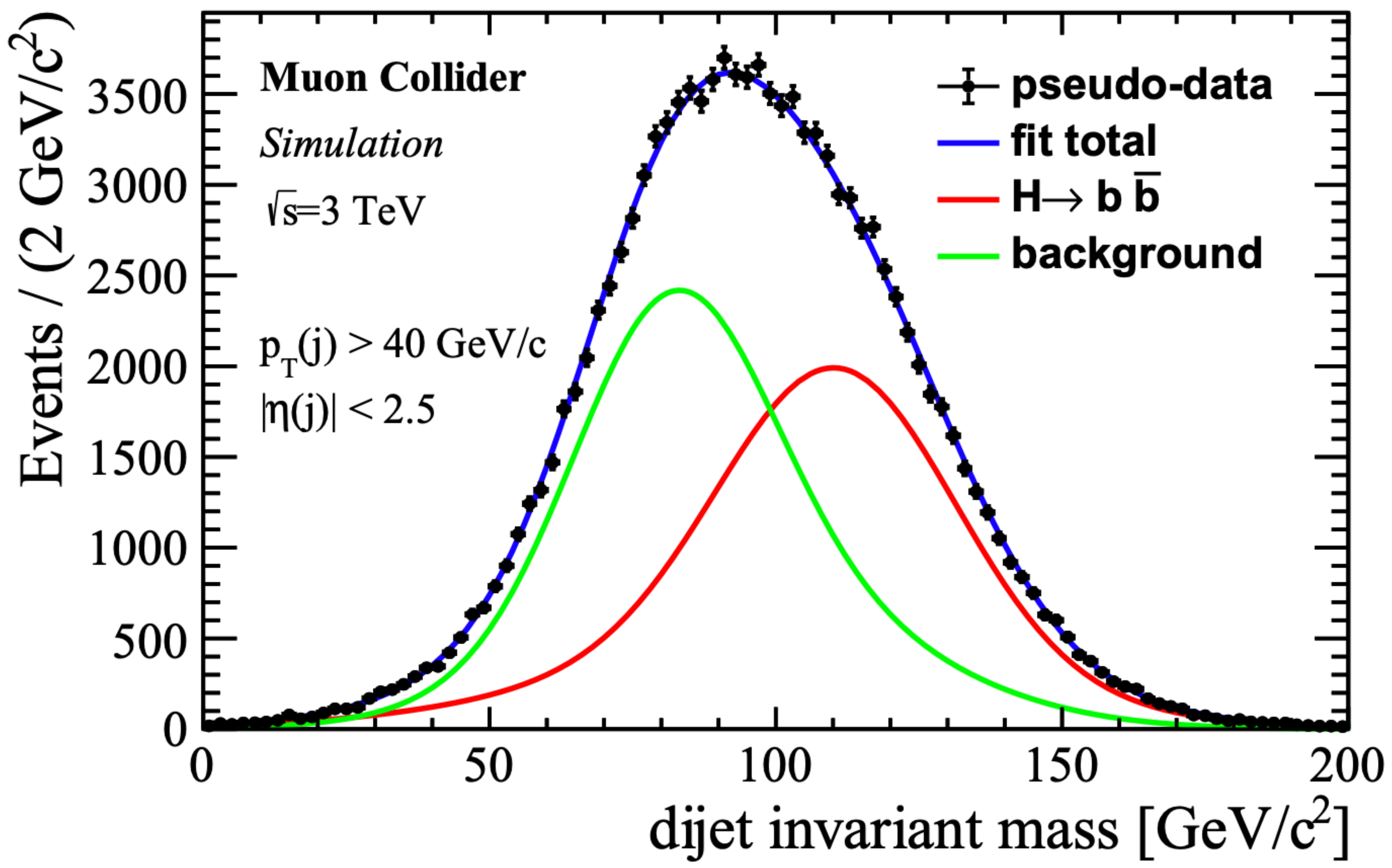
Current detector design taken from CLIC

ECAL: 5x5 mm² silicon sensor pads alternating with tungsten plates, resolution $10\,\%/\sqrt{E}$ for photons

HCAL: 30x30 mm² scintillating tiles alternating with steel absorbers, $35\,\%/\sqrt{E}$ for jets

works for 3 TeV, but for 10 need a new design





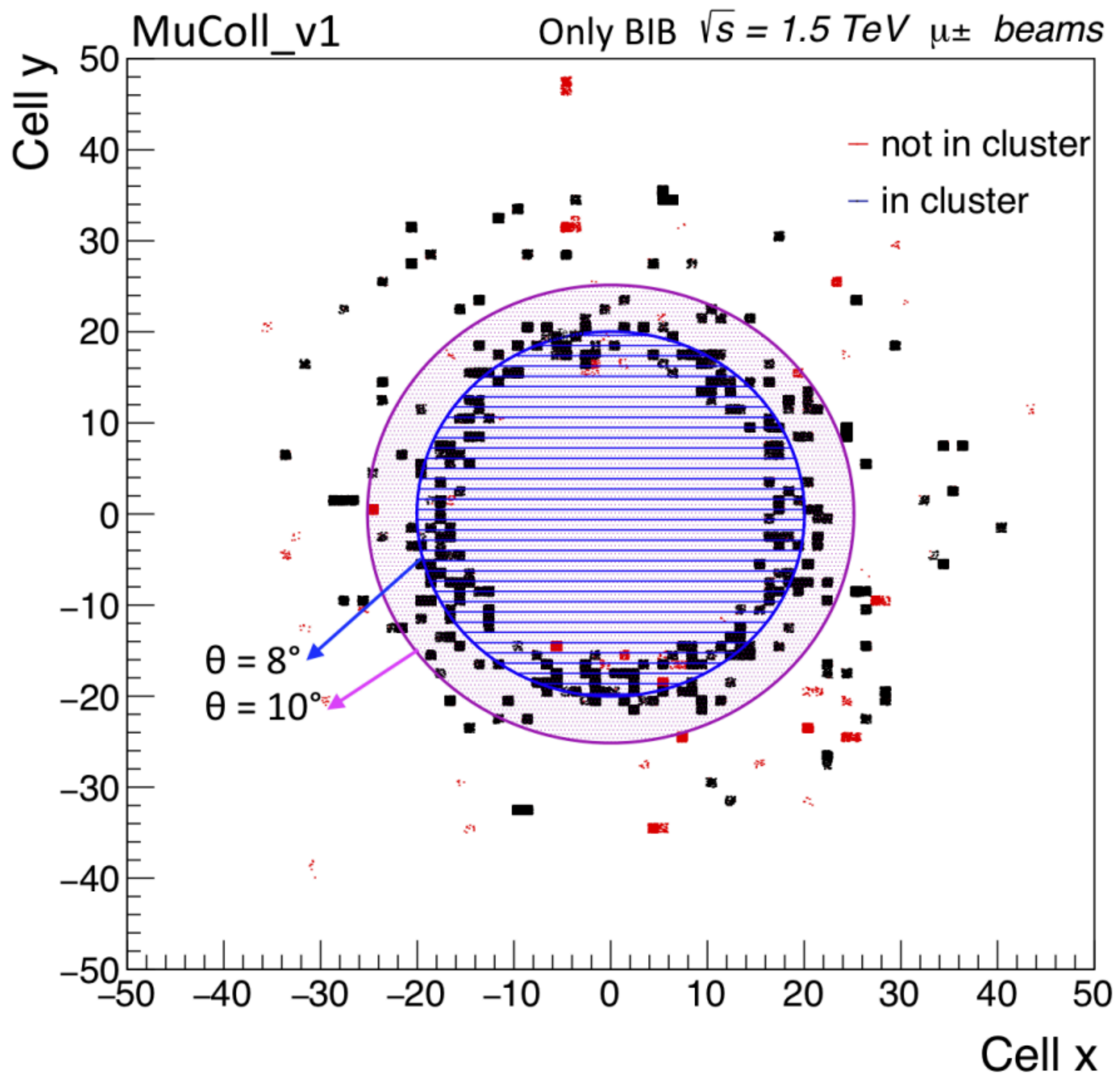
Detector Performance Report

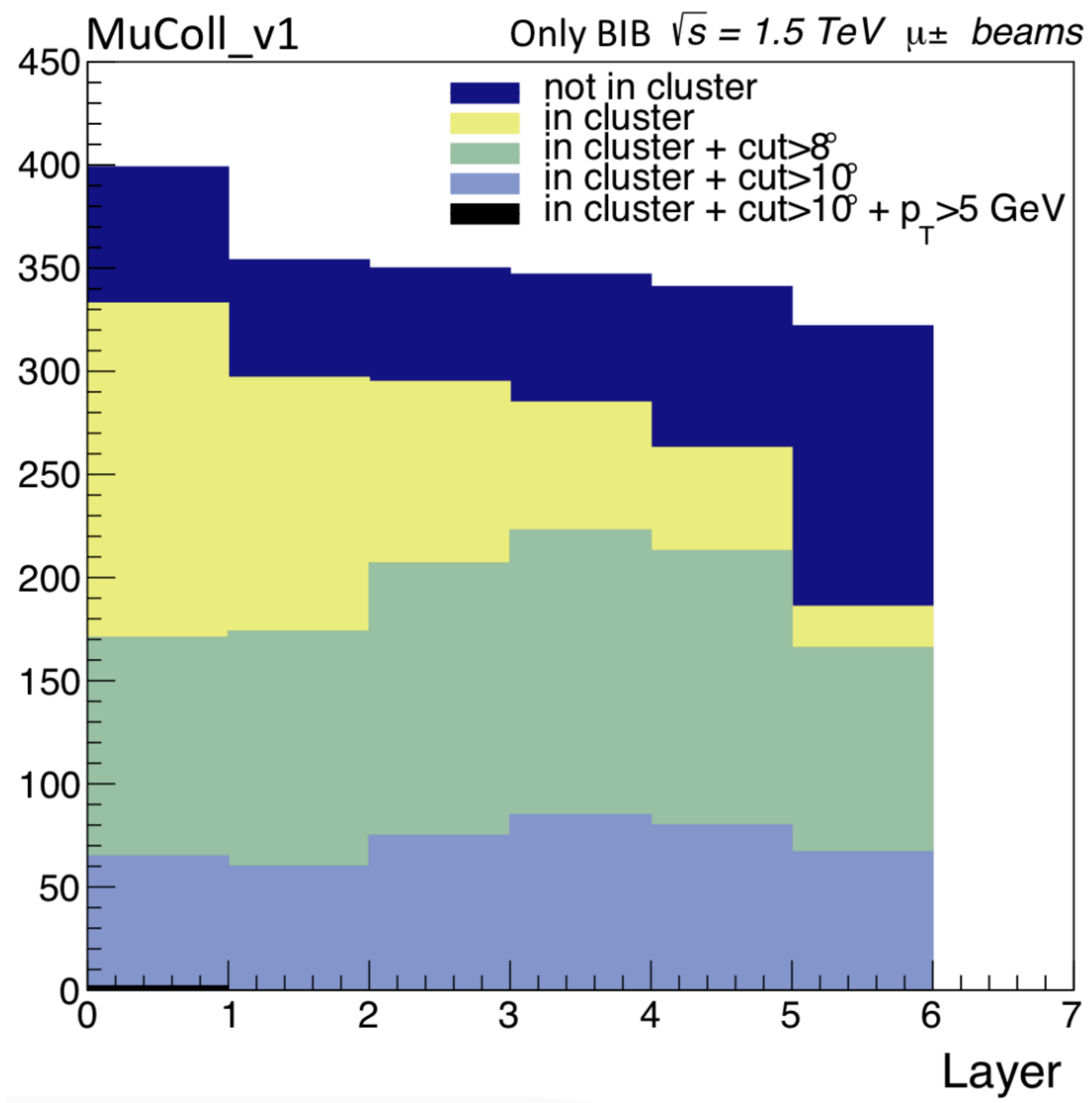
BIB in the muon detectors

greatly reduced following the calorimeter

largest challenges in the end-caps, but can reduce with geometric cuts and clustering

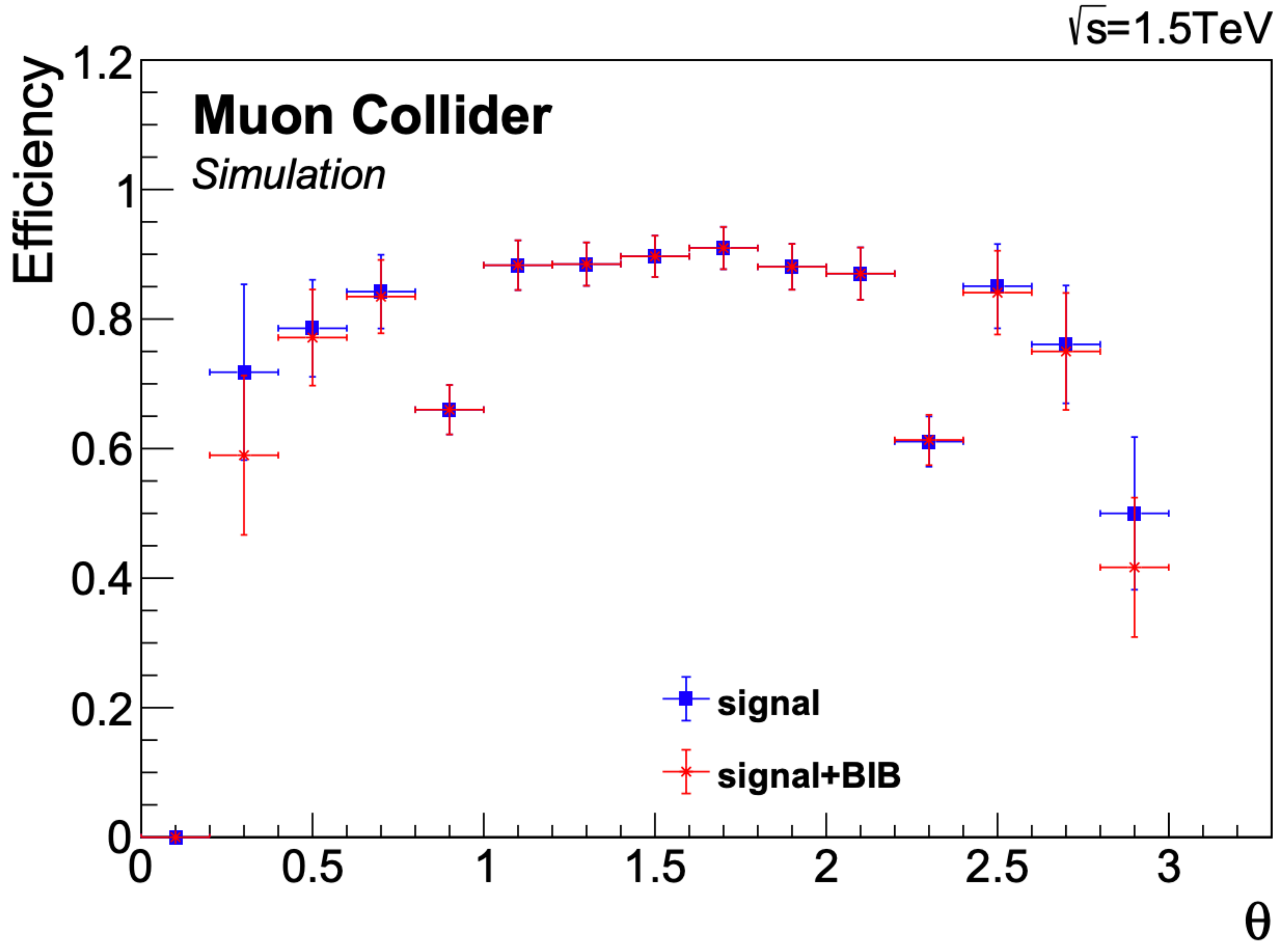
with p_T measurements after tracking, can reduce to almost nothing

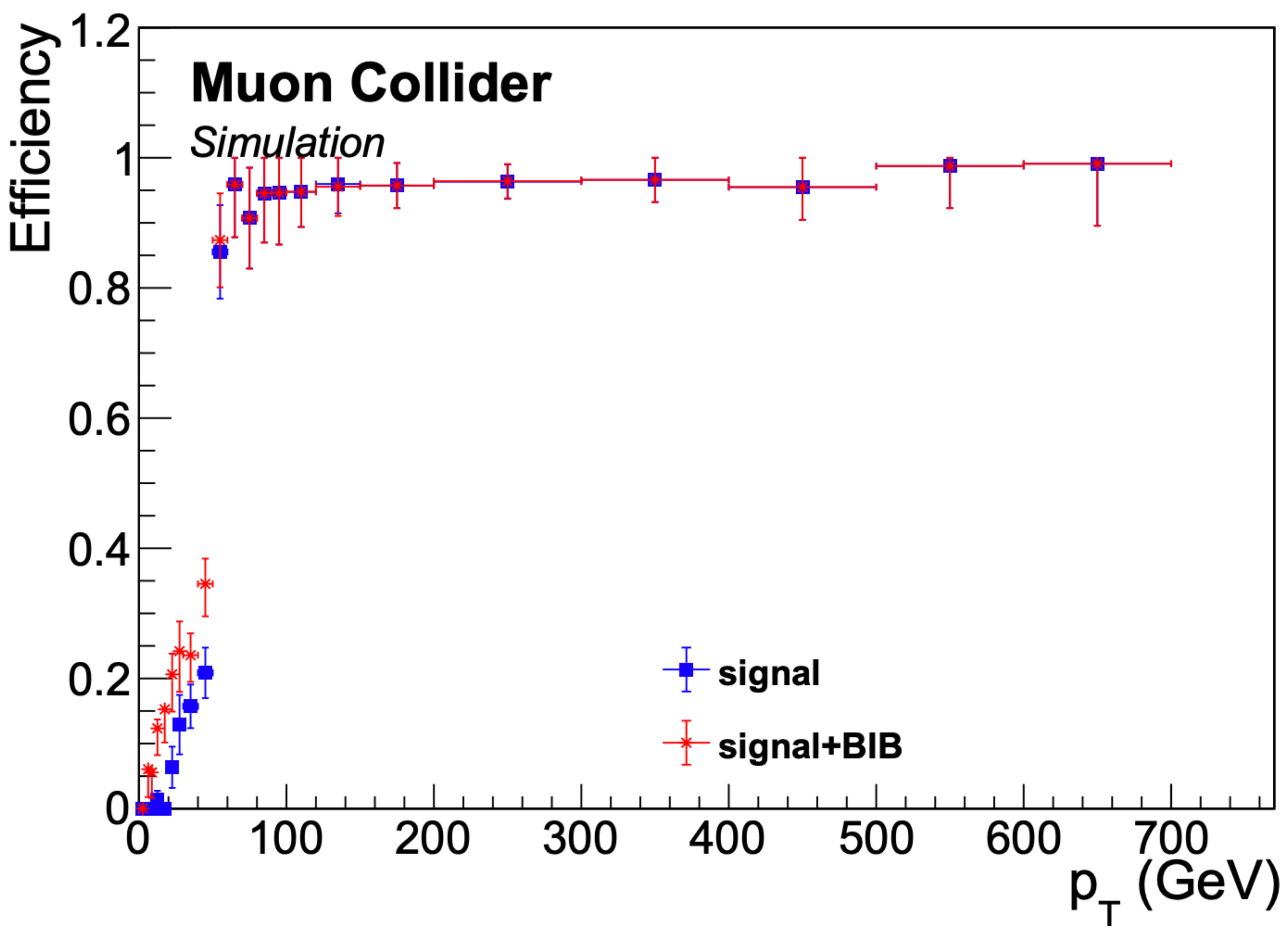


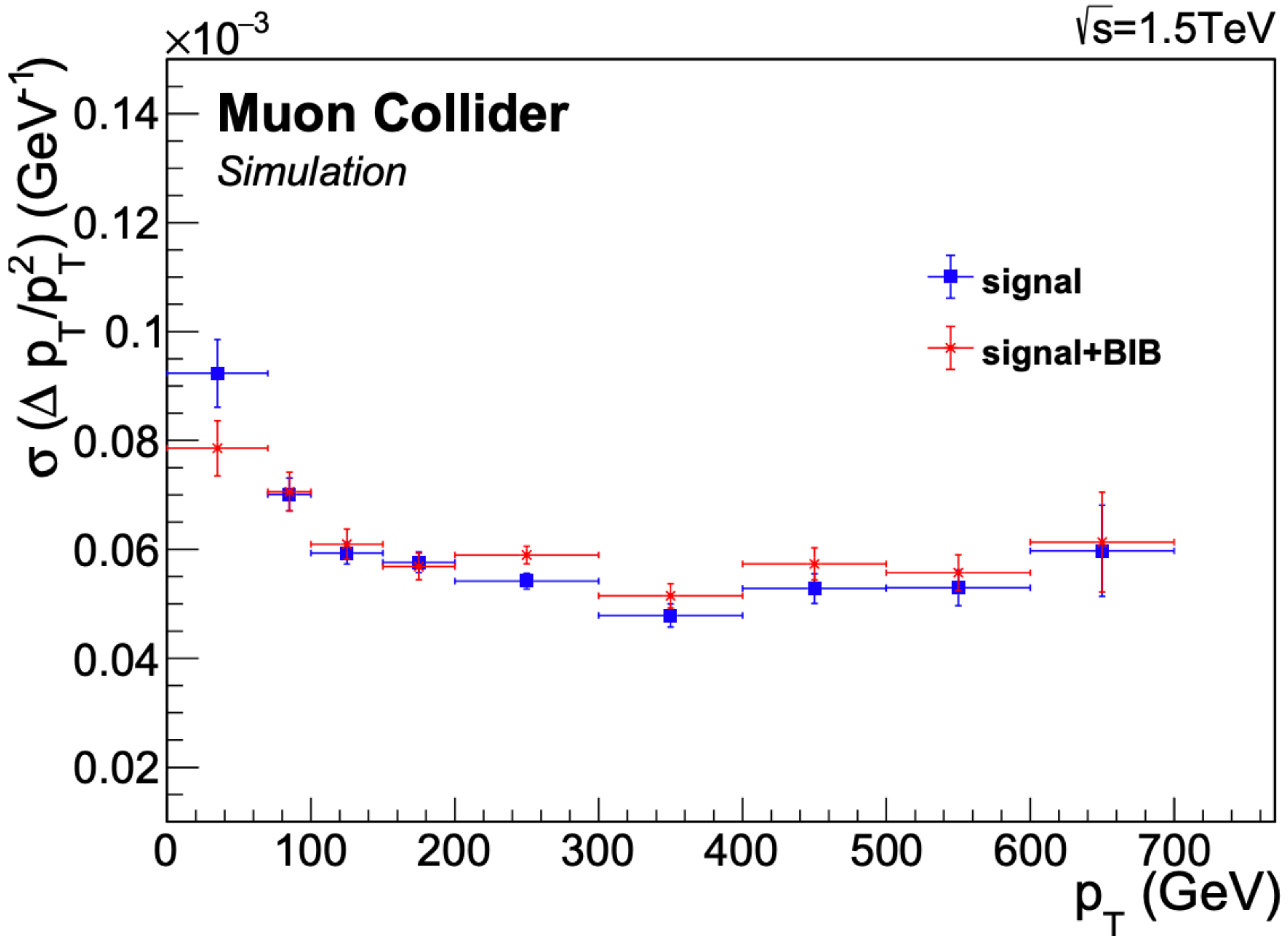


BIB in the muon detectors

muon efficiency and resolution not significantly affected by BIB







currently using CLIC designs: 6 layers of 30x30 mm² RPCs and an iron return yoke

needs consideration based on environmental impact of RPC gas mixture

plots assume O(ns) timing

Going forward

great tools to do studies on detector simulation

(see Nazar & Federico's talks)

exact conditions very dependent on MDI

(see Donatella's talk)

thorough studies of tracker performance and BIB mitigation,

but less thorough at higher R (especially needed in ECAL)

great progress, no show-stoppers

but lots of work to can be done to optimize performance, and we have the tools ready for more folks to get involved

Plus…

- And finally, a link to buy your own Muon Collider swag: https://www.redbubble.com/people/muon-collider/shop

Designs by Karri & me

Questions?